NAS7.010282
NASA-JPL
SSIC No. 9661

Naval Facilities Engineering Service Center (NFESC)

National Aeronautics and Space Administration

Jet Propulsion Laboratory

WORK PLAN

Pilot Study to Create an *In situ* Reactive Zone and Demonstrate Perchlorate Treatment at the Jet Propulsion Laboratory

October 10, 2002

ARCADIS

Infrastructure, buildings, environment, communications

ARCADIS

Work Plan

Pilot Study to Create an *In situ* Reactive Zone and Demonstrate Perchlorate Treatment at the Jet Propulsion Laboratory

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Our Ref.:
RN099455.0003.00001

Date:
October 10, 2002

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1. Introduction

1.1 The Naval Facilities Engineering Service Center Broad Agency Announcement Program and this Project

The Naval Facilities Engineering Service Center (NFESC) Broad Agency Announcement (BAA) program is a streamlined and flexible contracting approach tailored after the BAA program outlined in the Federal Acquisition Regulation (FAR). NFESC's BAA program promotes the demonstration of a wide range of innovative environmental technologies and methodologies that are either new, innovative, advance the state-of-the-art, or increase knowledge or understanding of a technology or methodology. To be eligible for consideration and possible contract award, the technology or methodology shall be in either the applied research (Category 6.2), advanced technology development (Category 6.3A), or demonstration and validation (Category 6.3B) stage of development. ARCADIS has been awarded a BAA project for the demonstration of *in situ* perchlorate bioremediation. With guidance from NFESC, a field demonstration site at the National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL) in Pasadena, California has been chosen. The project will consist of a demonstration of ARCADIS' *In Situ* Reactive Zone (IRZ) technology for the bioremediation of perchlorate in the saturated zone. Should a perchlorate source zone be identified in vadose zone soils during well installation, ARCADIS intends to initiate a vadose zone IRZ as a secondary objective.

1.2 Project Organization and Project Contact Information

The following is a list of the key contacts for those agencies involved in this remediation demonstration project.

Agency	Contact	Project Title
NASA Management Office Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, CA 91101	Peter Robles Jr. (818) 393-2920	NASA RPM
Naval Facilities Engineering Service Center 1100 23rd Avenue Port Hueneme, CA 93043	Richard Zuromski (805) 982-1488 (818) 354-5379	Project Manager

Agency	Contact	Project Title
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Naval Facilities Engineering Service Center 1100 23rd Avenue Port Hueneme, CA 93043	Kimberly Gates (805) 982-1656 (818) 354-2595	Alternate COTR/Assistant Project Manager
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U.S. Environmental Protection Agency, Region 9 75 Hawthorne Street San Francisco, CA 94105	Mark Ripperda (415) 972-3028	USEPA Representative
California Environmental Protection Agency Department of Toxic Substances Control 1011 North Grandview Avenue Glendale, CA 91201	Richard Gebert (818) 551-2859	Cal-EPA Representative
Regional Water Quality Control Board, Los Angeles Region 320 West 4th Street, Suite 200 Los Angeles, CA 90013	David Young (213) 576-6726	RWQCB Representative
ARCADIS 4915 Prospectus Drive, Suite F Durham, NC 27713	David Liles (919) 544-4535	ARCADIS Project Manager
ARCADIS 1400 N. Harbor Boulevard, Suite 700 Fullerton, CA 92835	Barry Molnaa (714) 278-0992	ARCADIS Technical Team Leader & Local Contact
ARCADIS 1400 N. Harbor Boulevard, Suite 700 Fullerton, CA 92835	Greg Fiol (714) 278-0992	ARCADIS Field Manager
ARCADIS 4915 Prospectus Drive, Suite F Durham, NC 27713	Libby Nessley (919) 544-4535	Quality Assurance Officer

Agency	Contact	Project Title
ARCADIS 4915 Prospectus Drive, Suite F Durham, NC 27713	Jerry Revis (919) 544-4535	Health & Safety Officer

1.3 Facility History

JPL is located along the southern edge of the San Gabriel Mountains and at the northern edge of the metropolitan Los Angeles area. JPL encompasses approximately 176 acres, of which approximately 156 acres are federally owned. The Arroyo Seco, an intermittent stream, lies immediately to the east of JPL. A series of surface impoundments, used for groundwater recharge, lies along the eastern margin of the Arroyo Seco stream channel.

Testing of liquid propellant rockets by a California Institute of Technology (CalTech) professor began in the Arroyo Seco in 1936. In July 1940, CalTech and U.S. Army Air Corps, entered into a contract under which CalTech agreed to study jet propulsion for airplanes. This contract was the first of a series of JPL contracts between CalTech and the United States that span the last 59 years for research and development work at JPL. By 1944, the facility officially became known as the Jet Propulsion Laboratory. In 1958, NASA took over control of JPL from the Army.

Much of the historic research conducted at JPL required the use of various chemicals and materials, including a variety of solvents, solid and liquid rocket propellants, and cooling-tower chemicals. Previous practice for the disposal of liquid and solid sanitary wastes involved discharge to "seepage pits". Some of the seepage pits may have received volatile organic compounds (VOCs) and other waste materials that are currently found in the groundwater. In the 1950's and 1960's, a sanitary sewer system was installed and the use of the seepage pits for waste disposal was discontinued.

In 1980, analyses of groundwater from Pasadena water-supply wells located in the Arroyo Seco, near JPL, revealed the presence of VOCs. Around the same time, VOCs were also detected in two Lincoln Avenue Water Company (Lincoln) supply wells. As a result, the Pasadena and Lincoln wells near JPL discontinued pumping between 1985 and 1989. In 1990, NASA funded the installation of a water treatment plant in the Arroyo Seco to treat these VOCs and allow the Pasadena wells to resume normal operations.

The groundwater beneath and downgradient of the JPL facility has been divided into two operable units, Operable Unit 1 (OU-1) for groundwater beneath JPL and extending to the east across the Arroyo Seco, and Operable Unit 3 (OU-3) for groundwater off-facility to the south of JPL and east of the Arroyo Seco. Operable Unit 2 (OU-2) pertains to the on-facility source investigation in soils.

Perchlorate is a non-volatile oxyanion of chlorine. JPL groundwater monitoring wells were sampled for perchlorate during the June/July 1997, September/October 1997 and January/February 1998 sampling events. Perchlorate was only detected in JPL monitoring wells after the January/February 1998 sampling events. Perchlorate was previously detected in an Arroyo Seco monitoring well in 1997. During the first half of 1997, the California Department of Health Services (CDHS) began an extensive screening for perchlorate in several hundred drinking water wells around the state (http://www.dhs.ca.gov/ps/ddwem/chemicals/perchl/earlyfindings.htm). As a result of the perchlorate detections that occurred during this screening, CDHS developed and released an improved analytical methodology for perchlorate on June 3, 1997 (http://www.dhs.ca.gov/ps/ddwem/chemicals/perchl/clo4meth.pdf). Based on the timing of JPL perchlorate analyses discussed in the OU-1/3 Remedial Investigation Report (RI) dated August 1999, ARCADIS anticipates that the bulk of early perchlorate analysis at JPL was conducted using the improved analytical methodology (Foster Wheeler Environmental Corporation, RI Report) and its associated lower detection limit of 4 µg/L.

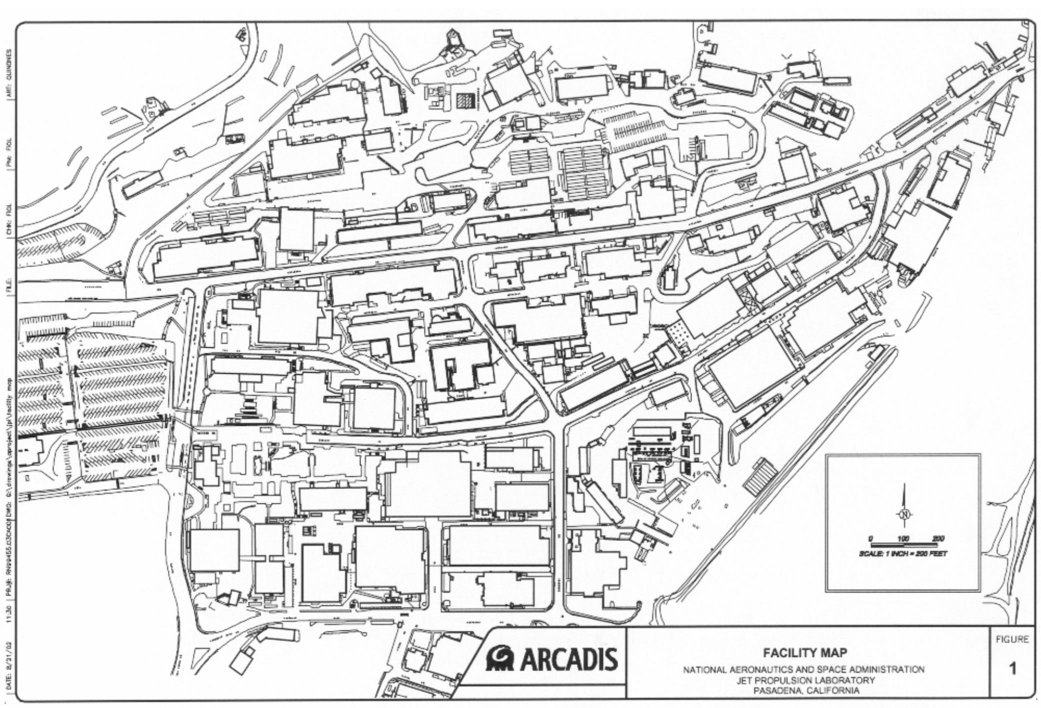
1.4 Description of Current Study

ARCADIS has developed a pilot study to meet the overall objective of assessing the feasibility of implementing *in situ* perchlorate source reduction at full-scale at the JPL facility (Figure 1). To accomplish this overall objective, the following tasks will be conducted as detailed below. The specific objectives of the pilot study are as follows.

- Conduct a microcosm study to verify that corn syrup is an appropriate electron donor to support perchlorate bioremediation in the aquifer at JPL and in any JPL vadose zone soils that are found to be contain elevated levels of perchlorate.
- Create a reactive reducing zone for perchlorate bioremediation within groundwater in an area directly upgradient and near monitoring well MW-7.
- If perchlorate is detected in vadose zone soils, create a reactive reducing zone for perchlorate bioremediation in soil overlying the perchlorate groundwater plume upgradient and near monitoring well MW-7.

- Monitor the hydrogeochemical changes in groundwater that occur over the course of treatment. Specifically, note the change in oxidation-reduction potential (ORP), dissolved oxygen (DO), hydrogen ion concentration (pH), and conductivity.
- Monitor changes in specific inorganic compounds—nitrate, perchlorate, ferrous iron, and sulfate.
- Monitor potential changes in the concentrations of specific organic compounds—chlorinated volatile organic compounds (cVOCs to include carbon tetrachloride, chloroform, trichloroethene, 1,2-dichloroethene, and vinyl chloride) and dissolved organic carbon (DOC).
- Obtain hydrologic transport information using an inorganic tracer (bromide). This information will be used to determine appropriate well spacing for full-scale.
- Determine the overall rate of perchlorate removal within the reactive zone.
- Determine the organic loading rate necessary to create reducing conditions amenable to perchlorate degradation.

Figure 1. JPL Facility Map



1.4.1 Nature and Extent

For the purposes of the pilot study, the portion of the site that will be evaluated for full-scale treatment is that area within the 500 µg/L isoconcentration contour for perchlorate developed from the most-recent groundwater-monitoring event. This area includes three monitoring wells (MW-7, MW-16, and MW-24) located in OU-1. In addition to elevated levels of perchlorate, groundwater in this area also includes elevated levels of cVOCs; primarily carbon tetrachloride. A comprehensive discussion of the nature and extent of chemicals in this area can be found in the OU-1/3 Remedial Investigation Report (RI) dated August 1999 (Foster Wheeler Environmental Corporation, RI Report).

The OU-1/3 RI concludes that there are multiple vadose zone perchlorate source areas located in the northeast portion of the JPL facility in and around monitoring wells MW-7, MW-16, and MW-24. The perchlorate source area contour, currently defined at 500 µg/L in the OU-1/3 RI, is contained within the facility boundaries.

1.4.2 IRZ Technology for Perchlorate Bioremediation

IRZ technology is founded on the concept of enhancing natural processes in a subsurface system to create conditions more conducive to degradation of the targeted compound of concern (COC). As such it can be classified as an enhanced bioremediation, anaerobic process.

IRZ technology relies on enhancing biologically mediated reactions by supplying additional organic carbon as an energy substrate to the subsurface and driving ORP to a lower, more strongly reduced state. This is accomplished by supplying the subsurface system with an organic substrate in the form of a common carbohydrate solution that serves as an electron donor. ARCADIS has utilized multiple carbohydrate substrates during IRZ implementation including molasses, high fructose corn syrup (corn syrup), and cheese whey. These substrates have proven to function as cost-effective, innocuous amendments for groundwater and have been accepted for injection by multiple state and federal regulatory agencies.

Indigenous heterotrophic microorganisms readily degrade the carbohydrate solution, which consists mostly of simple sugars. The rapid degradation process depletes the available dissolved oxygen contained in groundwater and the vadose zone, and drives the system to a more anaerobic and reduced state. The make-up of the bacterial community present in the subsurface prior to carbohydrate injection is shifted to bacterial species adapted to the changed anaerobic aquifer condition. Bacteria from the initial community remain and metabolize the carbohydrate solution to the extent that oxygen recharge permits. However, in the low oxygen environment, bacteria that are capable of utilizing alternate electron acceptors begin to occupy a more prominent role than in the previously aerobic soil environment. Bacterial processes such as nitrate reduction, iron reduction, and manganese reduction become increasingly dominant in the soil environment during this phase of IRZ development. With increasing amounts of injected electron donor, the ORP of the system can be driven further down into the –250 millivolt (mv) to –300 mv range. In this range, methanogenesis and sulfate reduction begin to co-occur as bacterial processes with carbon dioxide and sulfate being utilized as electron acceptors. Perchlorate reduction occurs in the same ORP range as nitrate reduction. It is ARCADIS' intent to control ORP to that characteristic of nitrate reduction through judicious electron donor dosing and subsequent monitoring. In the event of accidental over dosage, sulfate reduction and subsequent hydrogen sulfide release will be minimal due to the lack of sulfur in the electron donor chosen for this demonstration (more information on electron donor selection as it relates to sulfate reduction follows in Section 1.4.3). The production of hydrogen sulfide in a drinking water aquifer is discouraged.

Research has demonstrated that many nitrate reducing bacteria can also utilize perchlorate as a terminal electron acceptor with more than thirty microorganisms having been identified from diverse environments that are capable of degrading perchlorate (Coates 1999). Chlorate-reducing microorganisms have been identified as falling primarily into two groups: the *Dechlorimonas* group and the *Dechlorisoma* group. Members of these groups have been identified in nearly all environments screened in bench-scale studies, suggesting that these organisms may represent the predominant perchlorate reducing bacteria in the environment.

Bacterial reduction of perchlorate occurs as a result of anaerobic respiration. Anaerobic respiration couples the oxidation of an electron donor, such as an organic substrate (e.g., carbohydrates), or an inorganic molecule (e.g., hydrogen), to the reduction of a final electron acceptor (e.g., perchlorate). Under anaerobic conditions, oxidation of an electron donor requires the use of an alternative electron acceptor in place of oxygen, such as nitrate, manganese (IV), iron (III), or sulfate. As a highly oxidized compound (+7 oxidation state), perchlorate (ClO_4^-) has high potential for utilization as an alternate electron acceptor. For example, (Rikken et al., 1996) provided equations for the stoichiometric reaction of acetate with either oxygen or perchlorate as electron acceptors is as follows:

$$CH_3COO^- + 2O_2 \rightarrow 2\,HCO_3^- + H^+ \qquad (\Delta G^\theta = -844 \text{ kilojoules/mole or kJ/mol})$$

$$CH_3COO^- + ClO_4^- \rightarrow 2\,HCO_3^- + H^+ + Cl^- \qquad (\Delta G^\theta = -966 \text{ kJ/mol})$$

Comparing the Gibbs free-energy changes (ΔG^θ, kJ/mol acetate) it is evident that perchlorate reduction is energetically favorable. The reduction of perchlorate under anaerobic growth conditions has revealed that perchlorate can be completely reduced to chloride and oxygen (Rikken et al., 1996; Attaway and Smith, 1993; Wallace et al., 1996). Rikken et al., (1996) proposed a pathway for perchlorate reduction. The environmental science community has now largely accepted this pathway:

$$\underset{\text{Perchlorate}}{ClO_4^-} \rightarrow \underset{\text{chlorate}}{ClO_3^-} \rightarrow \underset{\text{chlorite}}{ClO_2^-} \rightarrow \underset{\text{chloride}}{Cl^- + O_2}$$

Through subsurface electron donor amendments, ARCADIS will encourage this biological process in the field by altering existing aerobic or mildly anoxic aquifers to anaerobic reactive zones. This creates suitable conditions for the biodegradation of perchlorate. Because perchlorate remediation is closely related to nitrate reduction processes, ARCADIS intends to dose the electron donor in a conservative manner initially. The intent of conservative electron donor dosing is to avoid the development of undesirable bacterial processes such as excess fermentation, which will result in the production of organic acids and potentially lower aquifer pH.

Once the desired aquifer microbiology has been attained, carefully timed subsequent additions of carbohydrate solution are utilized to support the altered aquifer microbiology until remediation is complete. This maintenance dosing occurs at planned, regular intervals to avoid fluctuations in the size of various metabolic components of the bacterial community. Unnecessary irregular dosing during the maintenance portion of a remediation program could complicate the biochemical chain through which energy substrates cycle in the IRZ. In addition, inconsistent dosing would complicate efforts to interpret aquifer microbiology using biogeochemical-monitoring parameters. The reactive zone performance following carbohydrate enhancement is measured by evaluating changes in the subsurface environment such as DO, ORP, pH, organic carbon, and conductance as well as changes in concentration of the target chemicals and degradation products.

When properly applied, ARCADIS has had only very limited challenges associated with biofouling near the injection well. Proper IRZ implementation results in the formation of an anaerobic zone within the aquifer. Due to the reduction in energy available under anaerobic conditions, the growth of bacteria present in an anaerobic setting is greatly curtailed. Nonetheless, if biofouling is encountered, it can be addressed by injecting a hydrogen peroxide solution. ARCADIS does not anticipate biofouling complications and will consult NASA prior to the injection of hydrogen peroxide as a remedy for biofouling.

When remediation is complete, as the carbohydrate in the subsurface is depleted, the bacteria enter a phase of endogenous metabolism, in which subsurface biomass is decreased to background levels. The end products of endogenous metabolism are water, carbon dioxide, mineralized nitrogen (N_2), and limited amounts of methane.

1.4.3 Carbohydrate Selection

ARCADIS reviewed the Strategic Environmental Research & Development Program (SERDP) bench-scale microcosm study. This microcosm study, which was executed by Envirogen, was designed to evaluate the relative effectiveness of various electron donors to facilitate perchlorate degradation. Two microcosm scenarios were evaluated. The first evaluated groundwater and sediment and the other evaluated pure groundwater. The results from the groundwater/sediment microcosms found that ethanol, lactate, molasses, yeast extract/ethanol, and acetate all performed equally as well (<5 µg/L) after 10 days of incubation. However, after 21 days of incubation, all of the microcosms with the exception of the killed control and benzoate microcosm had nondetectable concentrations of perchlorate. The groundwater microcosm found perchlorate reduction after day 10 in the molasses and yeast extract amended microcosms and reductions after 21 days in the acetate amended microcosm.

In addition to the SERDP Microcosm Study, ARCADIS reviewed microcosm studies conducted by Dr. Bruce Logan at Pennsylvania State University. The study evaluated the presence of perchlorate reducing microorganisms in the environment and their ability to use various substrates in the reduction of perchlorate. Lactate, acetate, and molasses were evaluated as electron donors. The results found that all of the electron donors stimulated the reduction of perchlorate in the environment. Lactate and molasses were found to stimulate the reduction faster than acetate, however, all the materials were found to work within timeframes that would be considered adequate for full-scale *in situ* remediation (i.e. within 20 days).

Corn syrup has been used previously by ARCADIS to demonstrate *in situ* reduction of perchlorate in groundwater. Corn syrup is a mixture of fructose, dextrose, and disaccharides. Corn syrup is composed primarily of the monosaccharide fructose. As an electron donor, corn syrup is believed to behave in a fashion similar to molasses. The primary sugar in molasses is the disaccharide, sucrose. Sucrose is composed of the two monosaccharides, glucose and fructose. Thus, ARCADIS believes that corn syrup will behave much like molasses as an electron donor in the aquifer.

Corn syrup is being recommended as the electron donor for this JPL demonstration because the groundwater being treated was considered a potable drinking water aquifer and there was concern about the addition of sulfur compounds (from molasses) that may create nuisance odors (i.e., hydrogen sulfide) as a result of the targeted reducing conditions. This precluded the use of molasses as a substrate. In addition, molasses contains a significant amount of nitrogen compounds that may tend to inhibit reduction of perchlorate in groundwater. There is evidence that nitrate competes with perchlorate. Based on these factors, an electron donor solution with low inorganic content should be selected for *in situ* reduction of perchlorate.

Of the electron donors evaluated to date, corn syrup, acetate, and lactate all have low inorganic content. Based on the SERDP microcosm lab studies conducted to date, it appears that many readily degradable organic compounds will stimulate perchlorate reduction. The key appears to be the removal of competing electron acceptors from the system (i.e., dissolved oxygen and nitrate). The reason for adding the electron donor is to remove the competing electron acceptors and create mildly reducing conditions on the order of 0 to –100 mV as measured with an ORP field instrument. Of the three electron donors discussed above, corn syrup is readily available from a variety of food distributors throughout the greater Los Angeles metropolitan area. In addition, corn syrup is a food grade substrate that can be added to the subsurface without significant regulatory concerns. Based on these criteria, corn syrup is recommended as the electron donor for the pilot study.

1.4.4 Milestones

The milestones for completion of the pilot test are as follows.

- Work plan Submittal.
- Work plan Approval.
- Well Installation.

- Baseline Sampling.
- Carbohydrate Addition.
- Establish Reduced (<-50 mV) Conditions within Aquifer.
- Progress Monitoring.
- Performance Monitoring.
- Final Sampling.
- Final Reporting.

1.4.5 Regulatory Environment

ARCADIS is following the development of USEPA and state-level regulations governing perchlorate remediation. Recently, the California Department of Health Services (DHS) set a drinking water Action Level for perchlorate at 4 µg/L. Previously, the Office of Environmental Health Hazard Assessment (OEHHA) established a Preliminary Health Goal (PHG) of 6 µg/L. California's governor recently signed a bill that will enforce the establishment of a perchlorate MCL by 2004.

The perchlorate action level will be considered as it pertains to the local groundwater setting in the demonstration area. ARCADIS has designed this demonstration with the intention of demonstrating the IRZ technology's potential for saturated zone perchlorate remediation. As a secondary objective, ARCADIS will apply the IRZ technology to any perchlorate containing portions of the vadose zone. After IRZ application to the saturated zone, its performance and cost of implementation will be compared with the results of any other comparable perchlorate remediation technologies for which results exist. As for any perchlorate source zone treatment that occurs in the vadose zone, ARCADIS believes that a source zone demonstration project can be successful without producing results that measure up perfectly to existing chemical specific regulatory closure standards.

1.5 Rationale for Location

The area proposed for the pilot study is the parking lot directly north of on-site monitoring well MW-7 (Figure 2). This area was chosen for the pilot study based on concentrations of perchlorate in groundwater (i.e., within the current 500 µg/L contour) and site accessibility. Also, the infrastructure necessary to conduct this pilot study is already present in the area near MW-7.

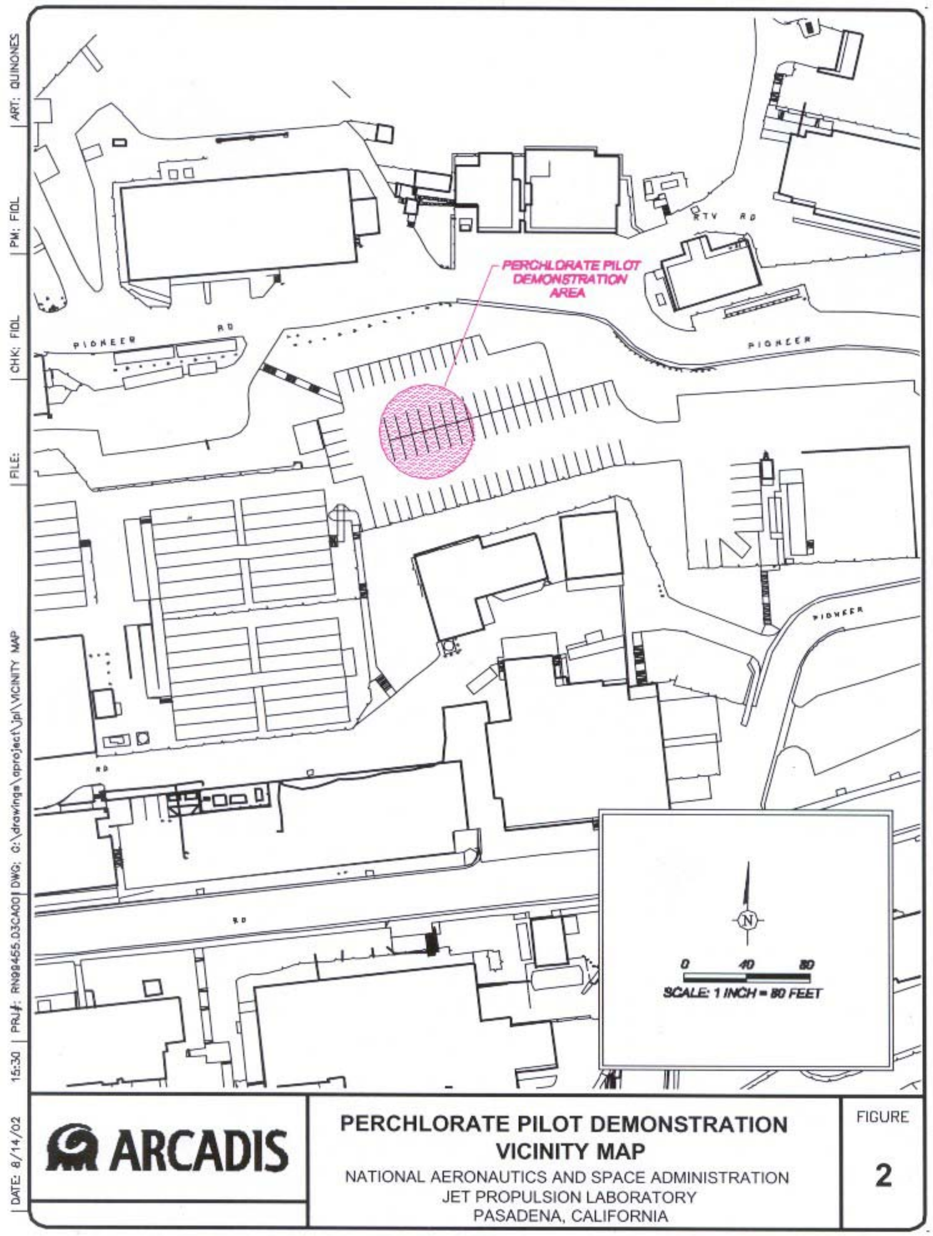


Figure 2. Perchlorate Pilot Demonstration Vicinity Map

2. Summary of Existing Information

2.1 Installation Environmental Setting

The JPL facility is located within the San Gabriel Valley in the eastern portion of Los Angeles County. It is bounded on the south, southwest, and southeast by east to west trending hills including the Repetto, San Raphael, Puente, and San Jose Hills (RWQCB, 1994). This hill system rises about 500 feet from the valley floor separating the southern edge of the San Gabriel Valley from the coastal plain of Los Angeles. The JPL facility is bounded to the north by the San Gabriel Mountains. The San Gabriel Mountains range from about 1,500 feet in elevation along their base to a maximum elevation of more than 10,000 feet above sea level. The San Gabriel Valley itself forms a broad plain that slopes generally to the south, downward from the base of the San Gabriel Mountains. The average slope of the valley floor is about 65 feet per mile. The rivers and tributaries that traverse the valley floor generally flow in a southerly direction. Almost all natural surface outflow from the San Gabriel Valley passes through Whittier Narrows (Foster Wheeler Environmental Corporation, RI Report for OU-1/3, 1999).

2.2 Facility-Specific Environmental Setting

2.2.1 Chemical Sources

As covered in Section 1.3, chemicals in groundwater at JPL result from historic research and waste disposal practices associated with the facility. VOCs present on-site include carbon tetrachloride, trichloroethene, 1,2 dichloroethane, and tetrachloroethene. Other chemicals at JPL include semi-volatile organic compounds (SVOCs), cyanide, petroleum hydrocarbons, and fluoride.

Specifically, this demonstration focuses on perchlorate, which is believed to originate from ammonium perchlorate used in solid rocket fuel, as well as from other potential upgradient sources. Improvements in perchlorate analytical chemistry methodologies occurred during implementation of the OU-1/3 RI. Quarterly groundwater monitoring indicates that levels of perchlorate have been found in at least Model Layer 1, and Model Layer 2 that threaten the utility of municipal production wells further downgradient. Based on a review of the OU-1/3 RI, ARCADIS expects that VOCs may also be chemicals of concern in the area of the facility where this demonstration will occur.

2.2.2 Geology

The geology in area of the existing shallow monitoring well MW-7 is discussed in this section. This area of the JPL facility is to be the site of this demonstration. A generalized discussion of the local and regional geology of the area has been included in the OU-1/3 RI (, Foster Wheeler Environmental Corporation, RI Report, August, 1999).

The stratigraphy surrounding MW-7 was evaluated by reviewing the OU-1/3 RI. MW-7 is located in the north-central portion of the JPL facility just south of an inferred fault. MW-7 was installed starting at an elevation of 1213 feet, and was completed at a total depth of 276 feet below land surface (bls). The OU-1/3 RI contains a published surface geologic map produced by the California Division of Mines and Geology (Smith, 1986). This surface geologic map confirms that MW-7 penetrates through the vadose zone and terminates in Model Layer 1 in the shallowest portion of the aquifer. Descriptions of each of the lithologic units beneath the study area in the upper layer of the Older Fanglomerate Series are presented below (Smith, 1986).

Overlying the Pacoima Formation throughout the study area is the Older Fanglomerate Series. This series is composed of light-brown to gray to dark-brown fluvial arkosic sands with abundant gravel and boulders. Smith (1986) divided the series into four stratigraphic members. Overall, there are no local compositional differences between the oldest (Qol) and youngest strata (Qo4) within this series. The predominant source of the Older Fanglomerate series is the crystalline rock complex exposed in the present day San Gabriel Mountains, although some reworked material from the Pacoima Formation is found in these sediments (Smith, 1986). The maximum exposed thickness of the Older Fanglomerate Series is about 150 feet along the east side of the Arroyo Seco near JPL (Smith, 1986). The age of this series ranges from late Pleistocene through Holocene. The age of the oldest strata is not precisely known because no fossil evidence has been found (Smith, 1986). For the purpose of the OU-1/3 RI, the Older Fanglomerate Series was divided into an upper and lower section, each representing a model layer (Layers 1 and 2). The division of the Older Fanglomerate Series was primarily based on how screens in each layer were affected by nearby pumping. Throughout the Older Fanglomerate Series, silt-rich intervals are present that appear to inhibit the vertical migration of groundwater during periods of pumping of the nearby production wells.

2.2.3 Groundwater

JPL is located in one of the four distinct groundwater basins found in the San Gabriel Valley called the Raymond Basin. Alluvial deposits at JPL comprise the groundwater reservoir and range in thickness up to about 1,100 feet. The Raymond Basin provides an important source of potable groundwater for many communities in the area including Pasadena, La Cañada-Flintridge, San Marino, Sierra Madre, Altadena, Alhambra, and Arcadia. The Raymond Basin is further divided into three separate hydrologic sub basins, the Pasadena Subarea, the Santa Anita Subarea, and the Monk Hill Sub basin (RWQCB, 1994). JPL is located in the Monk Hill Sub basin. In the Monk Hill Sub basin, the City of Pasadena and several other local water companies have installed a number of municipal water production wells to extract groundwater from the saturated sections of alluvial deposits (Foster Wheeler Environmental Corporation, OU-1/3 RI Report, 1999). The presence of municipal groundwater production wells near JPL and the presence of groundwater recharge basins (spreading grounds) near JPL in the Arroyo Seco significantly influences the local groundwater flow directions (Foster Wheeler Environmental Corporation, OU-1/3 RI Report, 1999).

Model Layer 1 (representing the uppermost portion of the aquifer), in which an anaerobic zone will be established during this demonstration, is equivalent to the upper portion of the Older Fanglomerate Series. This layer includes the water table and approximately the upper 75 to 100 feet of the aquifer. Underlying the alluvium in the subject area is the crystalline basement complex, comprised of the same general rock types that are exposed in the San Gabriel Mountains to the north. Groundwater in the basement rocks occurs only in bedrock fractures or joints. The aquifer below the facility is generally considered to be an unconfined, or water-table aquifer. However, due to the presence of relatively thin, silt-rich layers located throughout the alluvial aquifer that inhibit vertical flow of groundwater, vertical hydraulic head differences with depth are observed between screens in deep JPL multi-port monitoring wells located near production wells when the production wells are pumping. These vertical hydraulic head differences suggest the presence of semi-confined conditions (Foster Wheeler Environmental Corporation, OU-1/3 RI Report, 1999). These are the reasons fro the layered approach used in the groundwater model.

The underlying aquifer has also been divided into four "hydrogeologic" layers based on how silt-rich intervals influence the hydraulic heads in the aquifer during periods of pumping of the nearby municipal wells. The groundwater table has been measured in the JPL monitoring wells at depths ranging from approximately 22 to 270 feet below ground surface. This wide range of depth to groundwater can be related to geologic and topographic conditions around JPL, but it can also be related to affects from seasonal groundwater recharge at the nearby spreading grounds and affects of groundwater production from the nearby municipal production wells.

The groundwater chemistry of water from the underlying aquifer is documented in the OU-1/3 RI and summarized below. During the OU-1/3 RI, groundwater samples were analyzed for a suite of major anions and cations. The OU-1/3 RI used analytical results from these anion/cation analyses and general minerals data obtained from the CA DHS for the nearby municipal production wells to evaluate the general chemistry of the groundwater around JPL.

During the OU-1/3 RI, anion analyses included C1, SO_4, NO_3, and alkalinity (HCO_3 and CO_3). Cations analyses included Ca, Mg, Na, K, Fe. Total dissolved solids (TDS) analysis was also conducted. Because the Valley Water Company injects Colorado River water into the aquifer, a characterization of this water source was also included in the OU-1/3 RI. Following the preparation and review of Stiff diagrams during the OU-1/3 RI, Foster Wheeler Environmental Corporation judged that the majority of groundwater in the vicinity of JPL can be divided into three general types:

Type 1: Calcium-bicarbonate groundwater. Groundwater with Ca as the dominant cation and bicarbonate (HCO_3) as the dominant anion.

Type 2: Sodium-bicarbonate groundwater. Groundwater with Na as the dominant cation and HCO_3 as the dominant anion.

Type 3: Calcium-bicarbonate/chloride/sulfate groundwater. Groundwater with Ca as the dominant cation and HCO_3 the dominant anion, but with relatively elevated C1 andSO_4 concentrations. This water type consistently has relatively higher levels of TDS than the other two general types.

Groundwater Type 1 occupies three model layers in the area of MW-7 where this demonstration will be conducted.

2.2.4 Biology

The semi-arid Mediterranean climate of the San Gabriel Valley contributes to the dominance of chaparral in the foothill area around the JPL facility. Plants characteristic of chaparral include chamise, manzanita, wild lilac, scrub oak, and yucca. The coastal sage scrub plant community is mixed in with chaparral in some areas. Prevalent members of coastal sage scrub include California sagebrush, white sage, black sage, flat-toped buckwheat, and California encelia (http://parks.co.la.ca.us/eaton_narea.html).

A wide variety of animal life inhabits the foothills surrounding the JPL facility. Large mammalian species include opossum, desert cottontail, coyote, gray fox, raccoon, long-tailed weasel, striped skunk, bobcat, mountain lion and mule deer. Numerous rodents also inhabit the area. Many reptiles including salamanders, toads, frogs, lizards, and snakes populate the foothills as well (http://parks.co.la.ca.us/eaton_narea.html). One endangered reptile, the arroyo toad, inhabits the watersheds of Southern California. The arroyo toad is olive green or gray to light brown with a buff-white belly and is 2-3 inches in length. The predominately nocturnal arroyo toad prefers riparian habitats along sandy streambeds shaded by cottonwood, sycamore, and willow trees (http://sdnhm.org/fieldguide/herps/bufo-cal.html). The JPL facility has been cleared as a critical habitat for the arroyo toad by the U.S. Department of Fish and Game. Consequently, it is considered unlikely that ARCADIS and its subcontractors will encounter the arroyo toad on the JPL facility during this demonstration. Potentially dangerous species include black widow spiders, mountain lions, and rattlesnakes (http://parks.co.la.ca.us/eaton_narea.html).

3. Pilot Program Implementation

3.1 Permitting

Section 121 (e)(l) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) exempts EPA from having to obtain permits (local, state, or federal) for any Remedial Action (RA) conducted entirely o*n-site*; however, the "substantive requirements" of such permits must still be met. This applies to all permits, including environmental and building permits. However, the formal permitting process must be completed for any off-facility activities, as they are not exempt under CERCLA.

ARCADIS will abide by the substantive permitting requirements associated with Los Angeles County for well installation. In addition, ARCADIS will contact the Los Angeles Regional Water Quality Control Board (RWQCB) to confirm the CERCLA exemption for this project and to discuss the applicable sampling and monitoring required under the Waste Discharge Requirements General Approval Permit (WDR permit). If required by the RWQCB, ARCADIS will complete a WDR permit application and/or implement the WDR sampling and monitoring. Alternatively, ARCADIS will notify the RWQCB that the proposed IRZ sampling and monitoring program will be implemented. A copy of the RWQCB general WDR Permit is provided as Appendix 1. Health and safety during the pilot study will be conducted in accordance with the OSHA and Cal-OSHA requirements.

3.2 Access

3.2.1 Facility Requirements

At least four weeks prior to performing field activities, ARCADIS will submit a technical memorandum to NASA, which will provide a detailed discussion of the proposed fieldwork. NASA will then coordinate field activities with Caltech to ensure that the demonstration does not have any direct impacts on sensitive JPL operations. The ARCADIS field manager will conduct a site walk identifying work areas, equipment staging areas, and other coordination concerns that may need to be addressed.

Two weeks prior to the start of field activities, a final technical memorandum will be submitted to NASA. The revised memorandum will address any issues and/or concerns that were raised to NASA by Caltech. The following items will be addressed in the technical memorandum.

- Proposed field activities,
- Objective of field activities,
- Pre-fieldwork preparation (i.e. site drawing review, geophysical survey, etc.),
- Work area space requirements,
- Field activity schedule, and
- Scaled drawing identifying number of parking spaces needed, any road blockages.

3.2.2 Site Drawing Review

Prior to commencement of any field activities, available site drawings of the immediate work area will be reviewed to determine if any underground or overhead utilities may be present that will conflict with our activities. Utilities that may be present in the pilot test area include: domestic water, natural gas, sanitary sewer storm drains, compressed air, cooling tower water, nitrogen or other gaseous systems, electrical primary or secondary power lines, fire protection, and/or instrumentation cables. The information gathered during the document review will be used to focus the subsequent geophysical survey in areas of potential concern.

3.2.2.1 Geophysical Survey

3.2.3.1 Surface Geophysical Surveys

Surface geophysical techniques include, but are not limited to, ground penetrating radar (GPR), magnetometry, and electromagnetic techniques. The objectives of these techniques are to locate the boundaries of suspected or known underground metallic objects, electrically-conductive materials or volumes of disturbed soil. The areas to be surveyed are described and shown on site maps presented in Figures 1 and 2.

Surface geophysical surveys are conducted within predetermined grids defined by transect lines crossing each site or area of interest. The spacing of the grids is determined from the approximate dimensions of the features to be located. Specifically, the areas of interest include the well boring locations. Qualified individuals will conduct the surveys and will be supervised by a California Registered

Geophysicist (RGP). Location data, instrument numbers, calibration information, geophysical interpretation, and maps for all geophysical surveys shall be stored in project files.

The location and elevation of at least two points of the geophysical survey grid shall be surveyed according to the specifications of Section 3.9.

3.2.2.2 Electromagnetic Methods

Electromagnetic utility location methods are the most frequently employed techniques to detect utilities constructed of electrically conductive materials. Examples of these utilities include water, natural gas, telephone, electric, and fuel lines.

Typically, a radio frequency (RF) signal is induced into the electrically conductive conduit. This signal is propagated along its length and is detected above ground with a matched-frequency receiver. Often, underground water, electrical, oil-transmission, and telephone utilities radiate their own electromagnetic field and this field can be detected using an RF receiver alone. By detecting the signal maxima at several locations, the surface trace and burial depths of the underground utility can be determined.

Non-electrically conductive conduits, such as storm drains and sewers, are generally more difficult to detect with these methods. One technique to determine their surface trace is to insert a small RF transmitter. An RF receiver is then used at the surface to detect an area of maximum signal strength. A series of these areas or points yields the surface trace of the conduit.

A variety of utility locating instruments will be utilized to locate the utilities in the proposed work areas.

3.2.3 Employee Clearance

ARCADIS will include the names of its employees and those of authorized subcontractors in the field activities technical memorandum. After this memorandum is reviewed, the listed ARCADIS employees and subcontractors will require unescorted access to the portion of the JPL facility where the demonstration is sited. Any ARCADIS employee or subcontractor not listed in the field activities technical memorandum will be required to access the facility in accordance with JPL visitor procedures.

3.3 Well Design

One injection well (directly upgradient of MW-7) and five monitoring wells are proposed for the pilot area. Planned well spacing, orientation, and the amount of space required for installation and monitoring activities are shown in Figure 3, Figure 4, and Figure 5, respectively.

The injection well (IW-1) will be constructed as a single casing with multiple screened intervals throughout the unsaturated zone and a single screen in the upper saturated zone. The injection well will be constructed using 4-inch low-carbon steel casing and stainless steel wire wrapped screen. It has been assumed that the injection well will be installed to a maximum depth of 276 feet below surface. The results of expedited perchlorate soil analyses will be used to place 10-foot vadose zone well screens in vadose zone intervals that contain perchlorate. Vadose zone intervals where perchlorate is detected in soil samples collected as the drill rig was advanced will be screened as the drill bit is backed out of the well. The saturated zone will be screened from 10-feet above the potentiometric water surface to the total depth of 276 feet below grade (approximately 30 feet of screen). If perched groundwater is encountered during the installation of the injection well, it will be sampled and analyzed for perchlorate. A conceptual injection well design is included as Figure 6; however, actual screening of the well in the vadose zone will be based upon perchlorate analytical results from soil samples collected during the drilling of the well (See Section 3.5 for soil sampling procedures). Vadose zone intervals containing perched groundwater with perchlorate present will not be screened within the perched zone. Rather, a screen will be installed slightly above the perched water interval.

Following an injection(s) into a vadose zone perchlorate source area, the vadose zone monitoring wells will be sampled for the presence of water as a means of monitoring the radius of influence of fluid injection in the vadose zone. If sufficient aqueous sample is obtainable from the sump(s) installed in the vadose zone following an injection event, ARCADIS will analyze the water for perchlorate concentration and field parameters to determine perchlorate concentrations and IRZ zone characteristics. ARCADIS intends to be in daily contact with NASA during the final decision making process for vadose zone monitoring well installation so that joint decisions can be made regarding the actual depths of installation. It is our intent to remain flexible with regard to vadose zone well detail and use the flexibility to achieve radius of influence measurements for any injection events that become desirable in the vadose zone.

The vadose zone monitoring wells (clusters VMW1 and VMW2) will be installed after the injection well. The vadose zone monitoring wells will be used exclusively for evaluating subsurface migration of the injected fluid in the unsaturated zone (Figure 7). These vadose zone wells will be triple-nested and have been assumed to extend to a depth of approximately 105 feet below grade. This depth will have to be adjusted if it becomes desirable to inject electron donor solution into the vadose zone above or below 105 feet. Assuming that perchlorate source areas are detected in the upper 105 feet of the vadose zone, each of the vadose zone monitoring wells will be constructed so that three intervals have 10-foot screens beginning at 50, 70, and 90 feet below grade. A five-foot sump will be constructed of blank casing below each screened interval. These wells will be designed to collect any fluids that may migrate through the unsaturated zone during injection. Each well will be constructed of 2-inch PVC casing and screen. The vadose zone wells will be located crossgradient of the injection well, about 15 to 20 feet to each side. During the demonstration, water that collects in VMW1 and VMW2 following a vadose zone injection event will be removed from the well sumps, quantified and analyzed in the field for pH, ORP, and conductivity. If sample size allows, sump water samples will be analyzed for perchlorate, bromide and dissolved organic carbon (DOC). After sampling vadose monitoring well sumps, the sumps will be evacuated so that any sample collected subsequently will be distinct.

The three groundwater monitoring wells (IRZ MW1-3) have been assumed to extend to a maximum depth of 250 feet below surface (Figure 8). Each monitoring well will consist of a single 4-inch PVC casing with a single stainless steel screened interval placed approximately 10 feet above the potentiometric surface of groundwater and

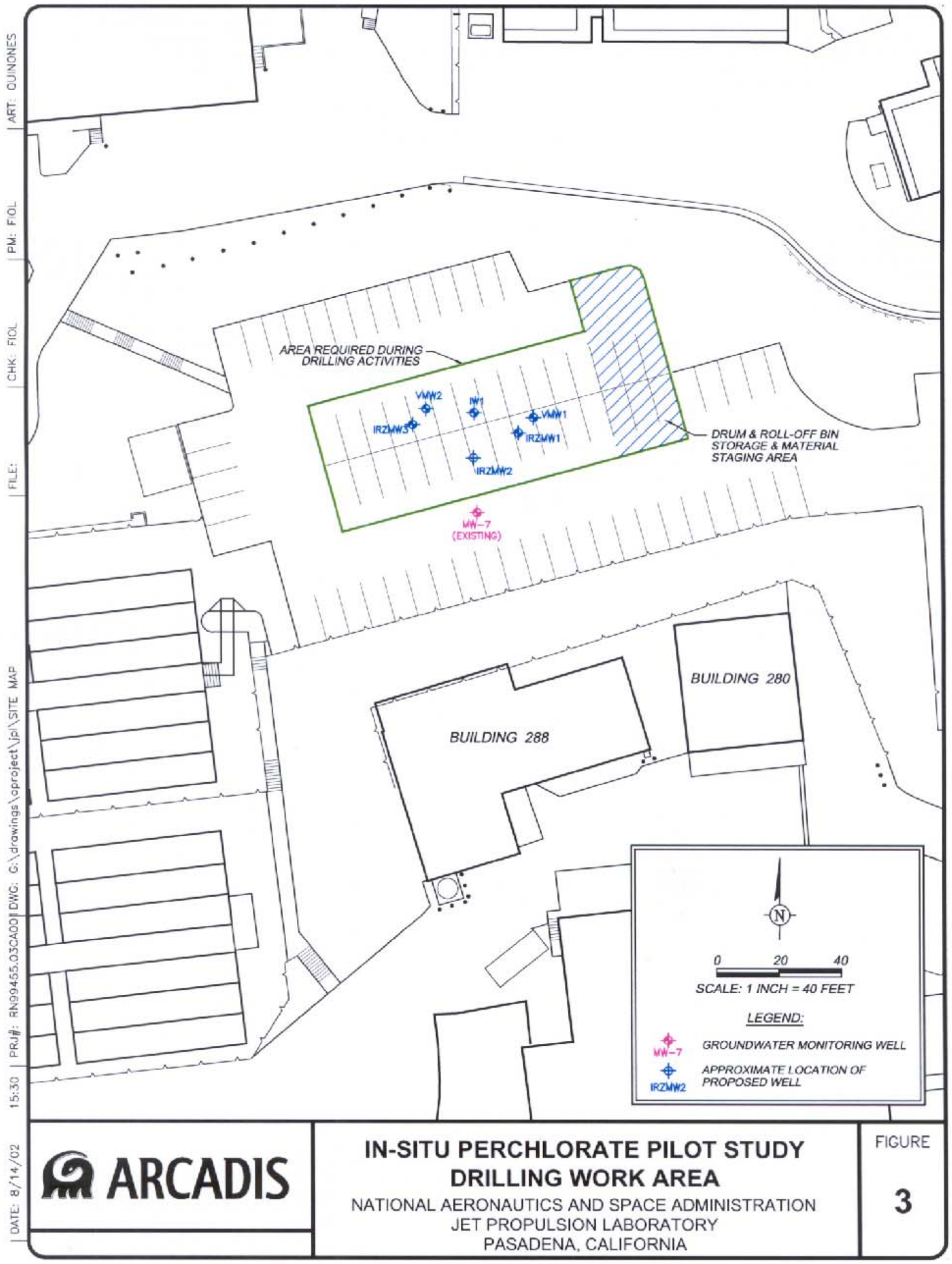


Figure 3. *In Situ* Perchlorate Pilot Study Drilling Work Area

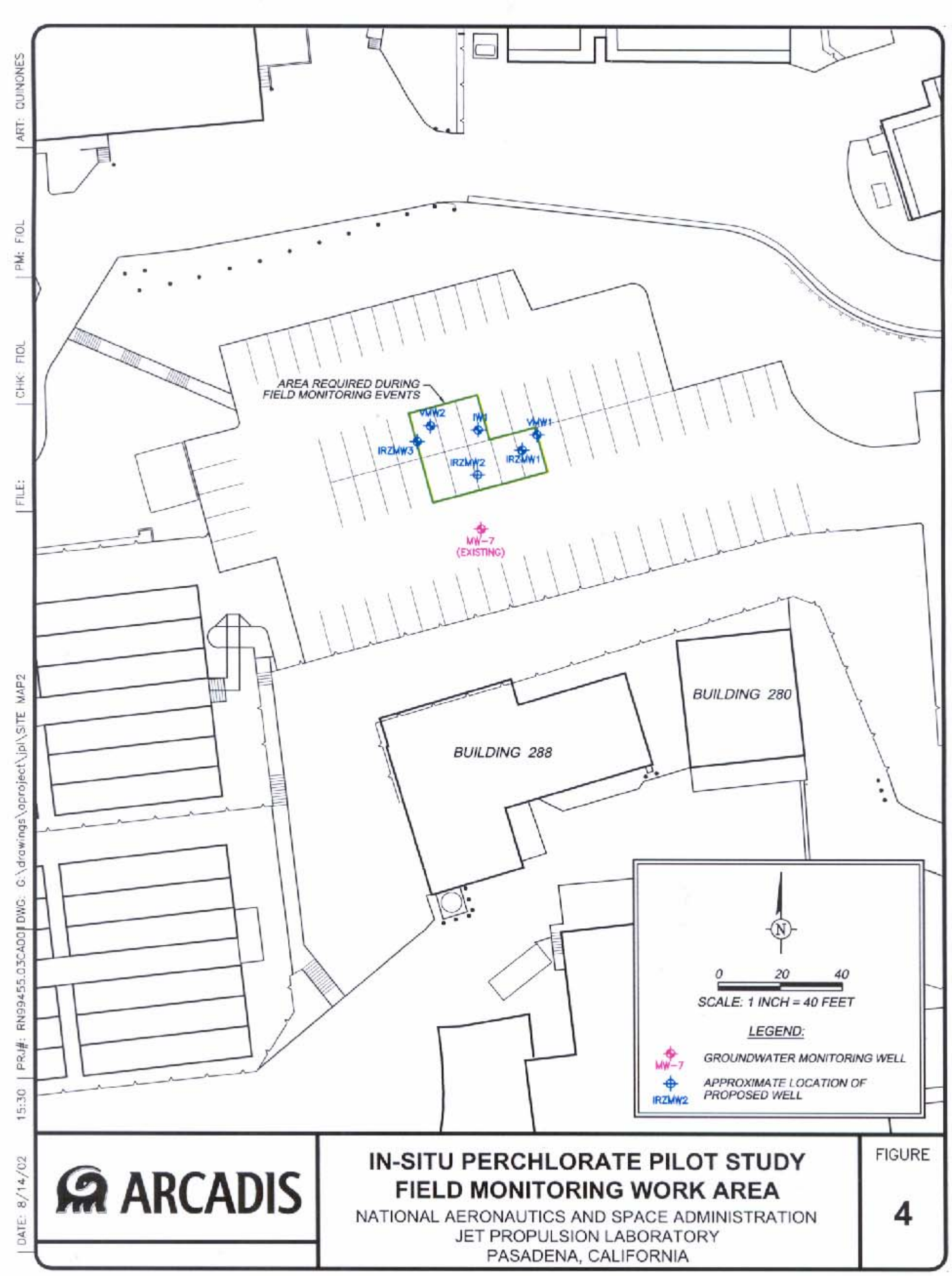


Figure 4. *In Situ* Perchlorate Pilot Study Field Monitoring Work Area

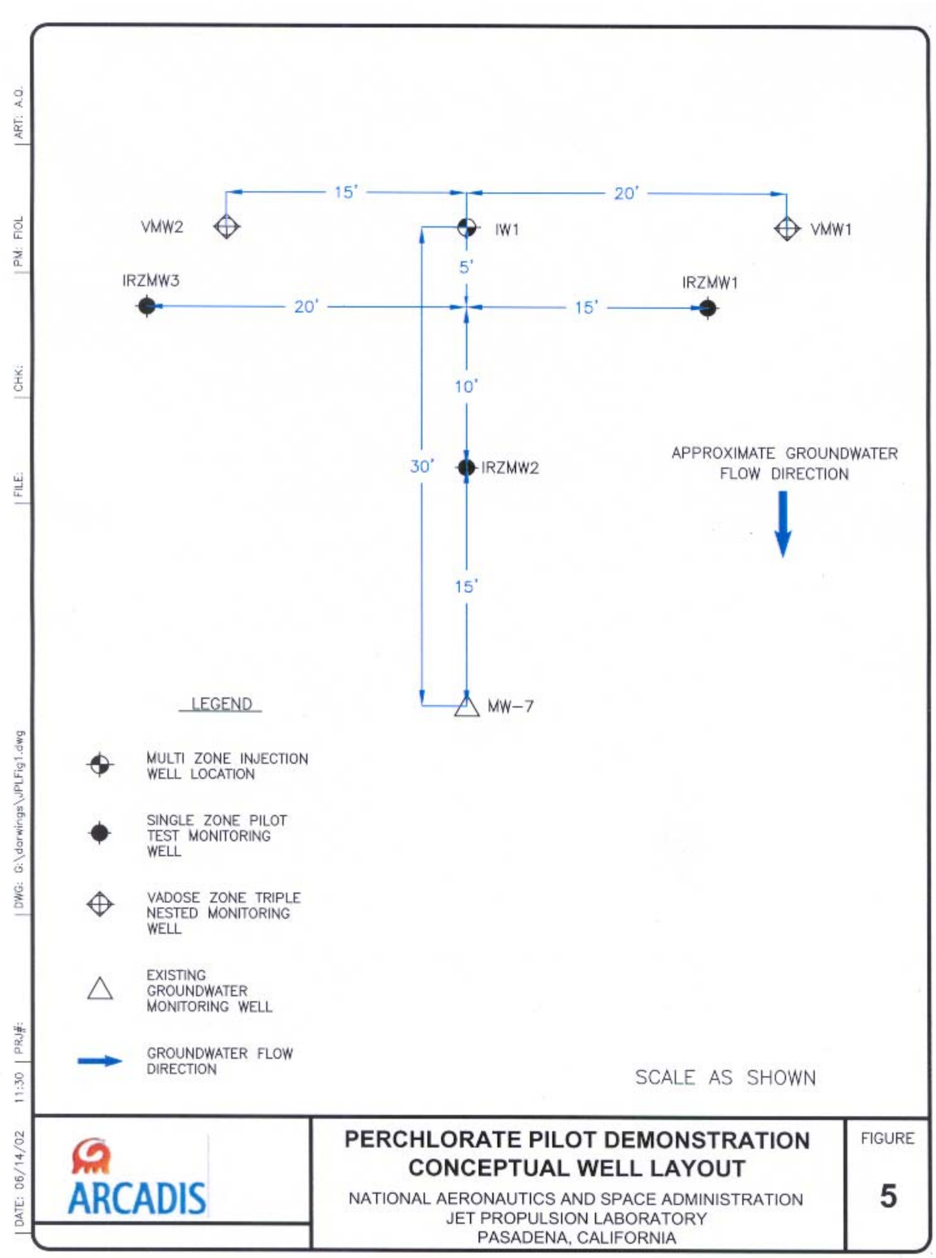


Figure 5. Perchlorate Pilot Demonstration Conceptual Well Layout

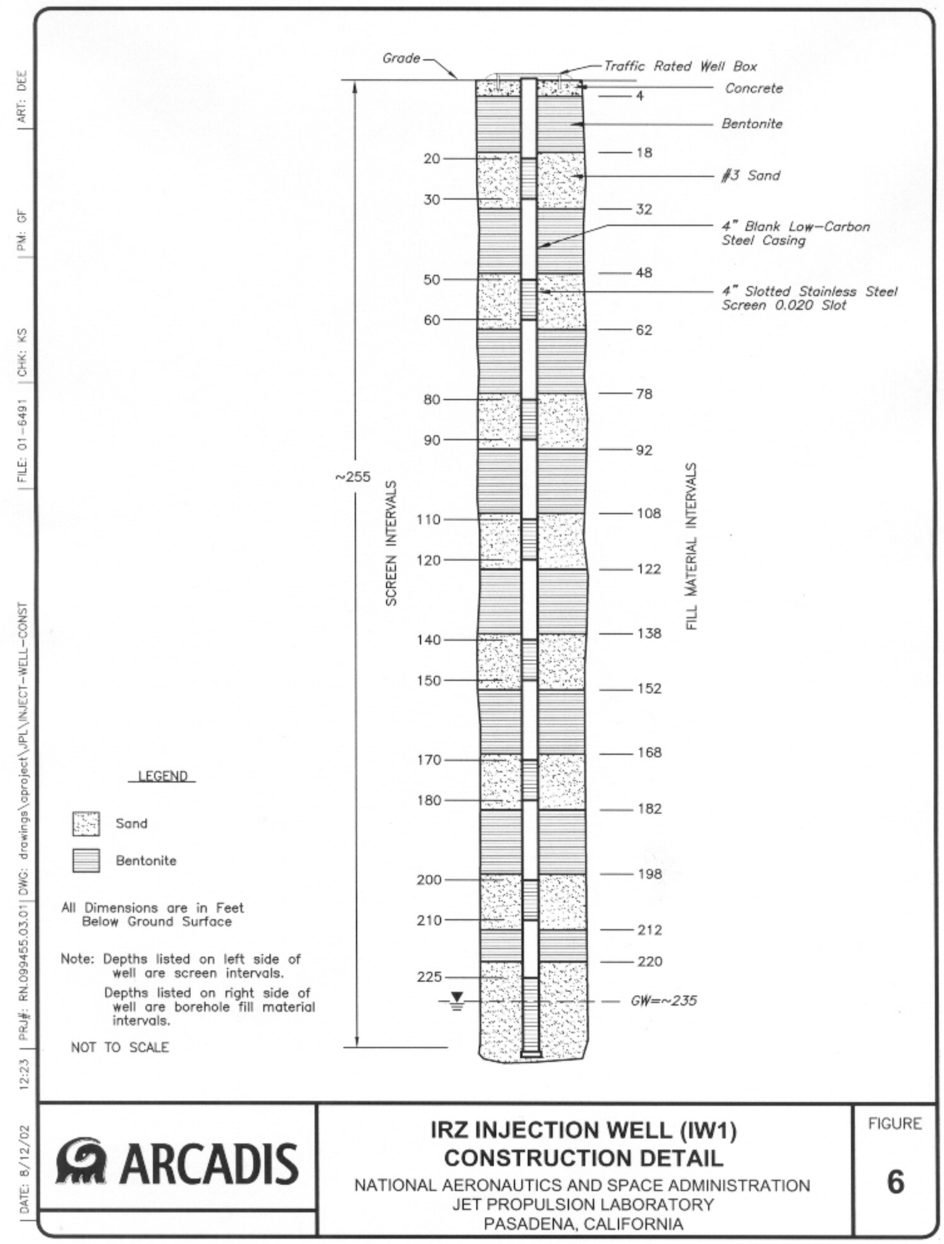


Figure 6. IRZ Injection Well (IW-1) Construction Detail

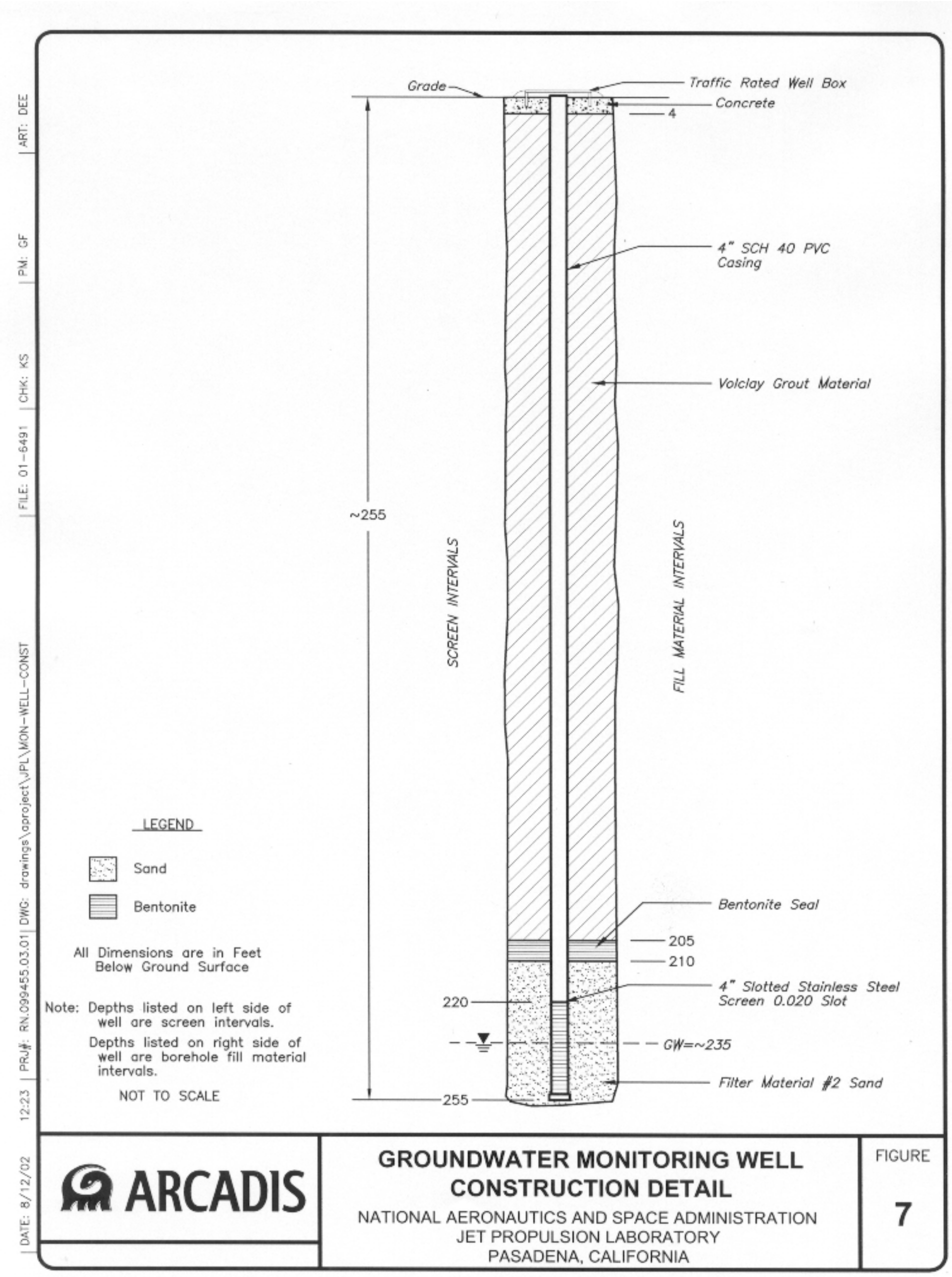


Figure 7. Groundwater Monitoring Well Construction Detail

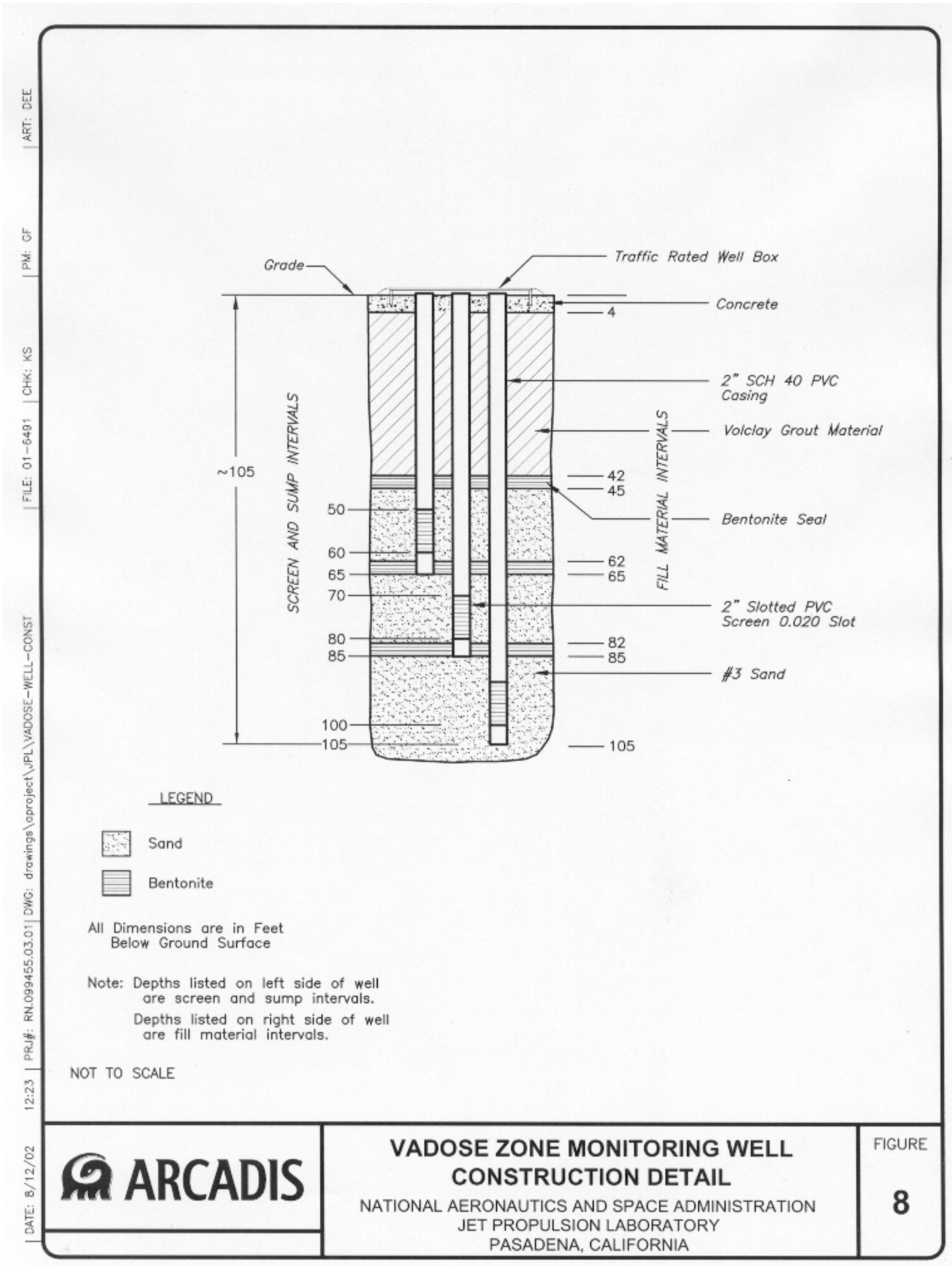


Figure 8. Vadose Zone Monitoring Well Construction Detail

extending to the total depth of the well (250 feet). It is estimated that no more than 30 feet of screen will be required to complete the installation of the individual saturated zone monitoring wells.

3.4 Drilling Technology

Sonic drilling has been selected for two of its fundamental advantages: speed and continuous core output. Sonic drilling is also referred to as vibratory drilling and rotasonic drilling. A sonic rig uses an oscillator or head with eccentric weights driven by hydraulic motors to generate high sinusoidal force in a rotating pipe drill. The top-mounted hydraulically powered drill head transmits the rotary power, hydraulic down pressure and vibratory power directly to the dual line of pipe. The frequency of vibration (generally between 50 and 120 cycles per second) of the drill bit and core barrel can be varied to allow for optimum penetration of subsurface materials. The dual string assembly allows advancement of casing with the inner casing used to collect samples. The inner drill pipe contains a core bit and represents the core barrel sampler while the outer pipe is used to prevent the collapse of the borehole and is used in the construction of monitoring wells.

The combination of forces advances the inner core barrel sampler through unconsolidated deposits and most consolidated formations without the use of water, mud, or air. Small amounts of air and water can be used to remove the material between the inner and outer casing. The inner drill pipe is always advanced in front of the outer drill pipe (typically 2 to 3 meters). Once the inner drill pipe is set, the outer drill pipe is advanced down over the inner drill pipe to hold the boring open. The inner drill pipe is mechanically lifted by the drill head to the surface for core sample recovery. The core sample is vibrated out of the inner drill pipe into a plastic sheath or stainless steel sample tray. The inner drill pipe is then advanced to the next sample interval.

3.5 Soil Sampling and Logging

As the injection well (IW-1) is being drilled, soil samples will be collected at ten-foot intervals. All injection soil samples will be sent to the analytical laboratory, although not all samples may be analyzed. While injection well soil samples will be collected every ten feet, initially the injection well soil samples collected every twenty feet will be analyzed for perchlorate concentration. Soil samples will be subjected to an aqueous extraction procedure prior to analysis by USEPA Method 314.0. The resulting extract will be subjected to perchlorate analysis using Method 314. Based upon the results of the analysis, other injection well soil samples may be selected for analysis to fill in data gaps. Injection well soil samples will be run on a 24-hour to 48-hour basis to provide data prior to constructing the well. Vadose zone soil horizons found to contain perchlorate during the installation of the injection well will be sampled during the subsequent installation of the two vadose zone monitoring wells. Lithologic samples will be examined in the field and logged according to the Unified Soil Classification System (USCS).

3.6 Well Development

Once the wells are installed, they will be developed by surging, bailing, and/or pumping. The objectives of well development are to remove sediment that may have accumulated during well installation, to consolidate the filter pack around the well screen, and to enhance the hydraulic connection between the target zone and the well. A minimum of 48 hours will pass between the completion of grouting and development. In most cases, a bailer will be used to remove sediment and turbid water from the bottom of the well. A surge block then will be used within each screened interval to flush the filter pack and screen. The well will be bailed again to remove sediment drawn into the well by the surging process until suspended sediment is minimized. Following the bailing and surging steps, the well will be further developed using pumping methods. The well will be developed at a higher pumping rate than the anticipated rate of future pumping for sampling, if feasible. During development, the turbidity of the water will be monitored and the pH, specific conductance, and temperature of the return water will be measured. Drawdown and recovery will be measured during and at the end of the development process, respectively, using an electric sounder. Well development will proceed until the following criteria are met:

- The return water is visibly clear or turbidity visually declines to a stable level.
- The sediment thickness remaining within the well is less than one percent of the screen length.
- A minimum removal of five well volumes. One well volume consists of standing water within the well as well as the saturated filter pack (assuming 30 percent porosity).
- Potable water used during well installation will be removed. A volume equal to five times the volume of water used during well installation will be removed in addition to the five well volumes described above.

- Stabilization criteria will be three consecutive measurements for which the specific conductance is within 10%, pH is within 0.1 units, and temperature is within 1 degree C.

Variations are not anticipated from these criteria, however any criteria that cannot reasonably be met in the field will be noted in the Daily Log Sheets as well as the well development sheets.

3.7 Laboratory Microcosm Study

ARCADIS will collect IW-1 soil samples from the saturated portion of the aquifer and any IW-1 vadose zone perchlorate source areas encountered and a groundwater sample to support a laboratory proof of concept study to support the use of corn syrup as an electron donor for the project. There are two justifications for this conservative approach for the IRZ demonstration. First, the previous SERDP funded microcosm study focused only on the saturated zone. Since the microbial ecology of any vadose zone perchlorate source areas can be expected to be different than the saturated zone, a laboratory study is warranted to validate the approach. Secondly, the previous SERDP funded microcosm study evaluated molasses, not corn syrup as an electron donor. Consequently, although the sugars in molasses and corn syrup are relatively similar, the conservative scientific approach dictates that corn syrup be evaluated at lab scale prior to field application. ARCADIS will prepare and distribute an appendix to this field pilot work plan covering the methods for this laboratory study. The laboratory study methodology will be modeled on that implemented by Envirogen during the SERDP funded laboratory screening program. The laboratory study will be conducted at ARCADIS' Durham, North Carolina Treatability Laboratory under direction of the ARCADIS project manager. Laboratory confirmation of corn syrup application on saturated zone soil samples and any vadose zone soil found to be impacted with perchlorate will take place during an expedited two to three week interval directly following well installation so as to minimally impact the schedule for corn syrup injection at JPL.

3.8 Field Sampling Methods

3.8.1 Soil Sampling

Similar sample collection methods for the injection and monitoring wells will be utilized.

Soil samples will be collected at every 10 feet and sent to the laboratory. Soil samples will be collected using a lined core barrel sampler, which allows for the collection of continuous soil cores. The following procedures will be used for the collection of soil samples:

1. Advance the inner drill pipe and core barrel sample to the desired sampling interval. The inner drill pipe is always advanced in front of the outer drill pipe.
2. Once the inner drill pipe is set, advance the outer drill pipe down over the inner pipe to hold the borehole open.
3. Mechanically lift the inner pipe and core barrel sampler to the surface using the drill head for core sample recovery.
4. Open the core barrel on a sheet of visqueen and record the lithology on the log of boring. The continuous soil core will be examined and logged based upon the USCS for each well and significant changes in lithology noted within the boring log.
5. Collect grab soil samples from the core barrel at the required depths.
6. Transfer the sample from the core barrels to pre-cleaned, 4-ounce glass jars using a pre-cleaned trowel.
7. Cap the jar(s) and wipe any moisture or soil from the outside of the jar(s).
8. Place a sample label on the jar, complete with the: Sample identification number, Sample collection date (month/day/year), Time of collection (24-hour clock), Site location, Project number, Sampler's initials, and analyses to be performed.
9. Place jar in a resealable bag.
10. Place resealable bag containing the sample in a cooler with bagged ice and packing material for shipment to the analytical laboratory.

3.8.2 Groundwater Sampling

Similar groundwater collection methods for the saturated zone injection and monitoring wells will be utilized.

Prior to initiating the pilot test, a baseline-sampling event will be conducted in the test area to determine a basis for which the results of IRZ pilot test will be compared. Baseline sampling will be conducted within 14 days of the completion of the wells and prior to carbohydrate injection. The parameters included during the baseline event and defined as a performance monitoring event are further discussed in Section 3.9.2. The following procedures will be used for the collection of groundwater samples:

1. The intake of the sampling tubing will be placed approximately half way into the saturated screen interval of each well to be samples throughout the purging and sampling intervals.

2. A submersible pump will be used to purge the wells at a low flow rate (typically, not to exceed 1.0 liter/minute) to produce minimal drawdown and turbidity during pumping. Purge water will be stored and disposed of appropriately based on procedures approved by NASA.

3. Groundwater parameters will be measured and recorded on a Groundwater Sampling Log. Groundwater samples for analyses will be collected when specific conductance, pH, and temperature have stabilized. DO and ORP will not be used as a stabilization parameter. Stabilization criteria will be three consecutive measurements for which the specific conductance is within 10%, pH is within 0.1 units, and temperature is within 1 ºC. Water quality parameters will be recorded within the Groundwater Sampling Log.

4. Hydrogen sulfide and ferrous iron will be measured in the field using colorimetric methods. The conductivity, pH, and turbidity meters will be calibrated per manufacturers instructions prior to the beginning of each day of sampling. The calibration will be checked after the measurements for all samples have been completed to monitor that the field instruments have remained in calibration throughout the process. Results of calibrations and final calibration checks will be recorded on the Daily Field Log.

3.8.3 Field Quality Control Samples

Field Quality Control (QC) samples will be collected and analyzed to assess the consistency and performance of the sampling program. Field QC samples for this project will consist of field duplicates. Field rinsate blanks and will not be required due to the sampling methods used for this project.

Field duplicates will consist of two samples (an original and a duplicate) of the same matrix collected at the same time and location, to the extent possible, using the same sampling techniques. Duplicates will be prepared and analyzed at a frequency of 1 per every 10 field samples (10 %). Field duplicates will receive unique sample numbers; therefore, the identity of the duplicate sample is unknown to the analytical laboratory. Exact locations of duplicate samples and their identification will be recorded in the Daily Log Sheets.

3.8.4 Liquid Waste Sampling

Liquid samples for waste characterization will be collected from each waste stream using disposable bailers. The samples will be collected in new, pre-cleaned bottle(s) with the proper preservative provided by the analytical laboratory. The samples will be labeled and packaged for laboratory submittal. The procedures utilized for sampling are as follows:

1. Sampler will wear new, clean, chemical-resistant disposable gloves.
2. The bailer will be secured to a nylon cord.
3. The bailer will be lowered into the 55-gallon drum and allowed to fill with water.
4. The bailer will be retrieved and the appropriate bottle(s) will be filled.
5. The bottles will be capped and wiped free of any moisture from the outside of the bottle(s).
6. The jar will be labeled complete with the: Sample identification number, Sample collection date (month/day/year), Time of collection (24-hour clock), Site location, Project number, Sampler’s initials, and analyses to be performed.
7. The bottle will be placed in a resealable bag.
8. The resealable bag will be placed in a cooler with bagged ice for shipment to the analytical laboratory.

3.8.5 Sampling Equipment Decontamination Procedures

If non-disposable sample equipment is used, the following procedures for decontamination of sampling equipment will be performed:

1. Wash with non-phosphate detergent.
2. Rinse with potable water.
3. Deionized/distilled water rinse (twice).

3.8.6 Sample Packaging and Shipment

Immediately after sample collection, sample labels will be affixed to each sample container. At the end of each day, the collected samples will be transported on ice to the laboratory under chain-of-custody procedures with custody seals on the sample coolers.

3.8.7 Field Documentation

At a minimum, sampling information will be recorded on a chain-of-custody form and in the Daily Log Sheets. Both documents will be completed in the field at the time of sample collection. All entries will be legible and will be recorded in indelible blue ink.

Changes or corrections on any project documentation will be made by crossing out the item with a single line, initialing (by person performing the correction), and dating the correction. The original item, although erroneous, must remain legible beneath the cross-out. The new information should be written above the crossed-out item. Corrections must be written clearly and legibly with indelible ink.

3.8.8 Chain-of-Custody Documentation

Chain-of-Custody (COC) documentation is required for each sample to track sample collection, shipment, laboratory receipt, custody, and disposal. The COC form will be used to record the samples taken and the analyses requested. Information recorded will include:

- Client name, address, telephone number, and fax number
- Name of primary contact
- Name of analytical laboratory
- Site name
- Project name
- Project number
- Sample identification number
- Time and date of sample collection
- Container size and type
- Type of sample (i.e., soil or water)
- Preservatives
- Analyses requested
- Sampler's signature
- Any other project-specific instructions to the laboratory

The top two copies of the completed COC form will accompany the samples to the analytical laboratory, and the remaining copy will be kept for project files.

Each individual who takes possession of the samples will sign the COC form. A sample is considered to be in one's custody if it is:

- In actual possession or in view of the person who collected the sample;
- Locked in a secure area; or
- Placed in an area restricted to authorized personnel.

If a commercial shipping company transports the samples to an analytical laboratory, the waybill or airbill will be noted on the COC form. The waybill or airbill serves as an extension of the COC.

3.8.9 Daily Log Sheets

Proper and accurate documentation within the field Daily Log Sheets will be performed to prevent misidentification of samples and to help in the interpretation of the analytical results. Daily Log Sheets are assigned to the specific person who is responsible for the recording of information. All Daily Log Sheets will be signed and dated by this person prior to the initiation of fieldwork. Additionally, the project number, name and location will be recorded at the top of each sheet. All information recorded on these log sheets will be made by the designated person in indelible blue ink. At the end of each workday, the Daily Log Sheets will be signed and dated by the person. Unused portions of the sheets will be crossed out, signed and dated.

If it is necessary to transfer the Daily Log Sheets to another person during the course of field work, the person relinquishing the Daily Log Sheets will sign and date the last line of recorded information at the time it is transferred, and the person receiving the Daily Log Sheets will do the same.

Information recorded in the Daily Log Sheets will include the following:

- Project name and location;
- Date and time;
- General weather information;
- Work performed;
- Field observations;
- Sampling performed; including specifics such as location, type of samples, type of analyses, and sample identification;
- Field analyses performed; including results, instrument check, any problems, and calibration records for the field instrumentation;
- Descriptions of deviations from the Work Plan;
- Problem encountered and corrective actions taken;
- Identification of primary field and QC samples;
- QC activities; and
- Verbal or written instructions.

3.9 Waste Handling

Waste generated during the drilling activities will include solid and liquid waste. Solid waste will consist of the soil cuttings generated during drilling activities that will be sampled for waste characterization during the drilling activities. Soil will be stored on-site in labeled Department of Transportation (DOT) approved 55-gallon drums or roll-off bins in a secure storage area. Liquid waste generated during the drilling activities will consist of decontamination water generated as part of the decontamination procedures associated with drilling and sample collection as well as water removed from the wells during the well development. The liquid waste will be collected and temporarily stored in labeled DOT approved 55-gallon drums on-site within the same secure storage area as the solid waste. A composite sample of liquid waste from each waste stream will be collected and characterized.

Upon review of the analytical results for the wastes, the wastes will be classified, and transportation and disposal options will be evaluated. If off-site transportation and disposal is required, ARCADIS will secure a licensed waste disposal contractor, prepare manifests, schedule the removal of the waste, and acquire certificates of disposal or certificates of treatment. Disposal activities will be coordinated with the authorized representative from JPL. All applicable certificates, laboratory results and Uniform Hazardous Waste Manifests will be submitted to the JPL representative for review and signature prior to off-site disposal of any waste material.

3.10 Surveying

Upon completion of field activities, a State of California licensed land surveyor will locate all of the new wells. The surveyor will determine each well's map coordinates referenced either to a Universal Transverse Mercator (UTM) grid or the State Planar Coordinate System (SPCS). These surveys will be connected to the UTM or SPCS by third order, Class II control surveys. The surveyed horizontal coordinates for all wells will have an accuracy of one foot within the chosen system.

Elevations for the adjacent ground surface and a designated point on the rim (north side) of the uncapped well casing for each monitoring well will be surveyed to within 0.01 feet and referenced to the National Vertical Datum of 1929 (NGVD). These surveys will be connected by third order leveling to the NGVD.

3.10.1 Operation & Maintenance

The operation and maintenance of the pilot study system is discussed in the following sections. The O&M activities are presented as discrete events for purposes of discussion. However, actual implementation of the O&M activities described herein may be conducted together.

The O&M of the pilot system can be separated into four distinct forms of monitoring: 1) Baseline sampling; 2) Progress monitoring; 3) Performance monitoring; and 4) Final sampling. The objective of the baseline sampling event is to determine the state of the system prior to addition of the carbohydrate solution. The baseline sampling event is conducted immediately following installation of the well system. Progress monitoring uses simple field monitoring methods to quickly evaluate the subsurface conditions and determine if reducing conditions are being created in the subsurface and provide the necessary data to evaluate the need for further carbohydrate addition. Performance monitoring includes laboratory analysis of the primary target compound perchlorate. Secondary affects may occur for cVOCs so USEPA Method 8260 will be utilized to provide concentration data for carbon tetrachloride and its daughter product chloroform and trichloroethene and its daughter products 1.2-dichloroethene and vinyl chloride. Analytical measurements will provide direct confirmation that the pilot system is removing perchlorate from the subsurface. Final sampling will provide an indication about the practical limitations of IRZ implementation for comparison to regulatory guidance on perchlorate.

Table 1 summarizes the extent and timing of sample collection by well type and analytical methods for the proposed performance monitoring events. All analytical methods are consistent with United States Environmental Protection Agency methods or are documented in prior environmental work at the JPL facility. The scope of work for each monitoring category is summarized in the following sections.

3.10.2 Baseline Data Collection

To establish baseline conditions within the aquifer (i.e., groundwater conditions prior to the start of the demonstration), an initial round of groundwater elevation measurements and groundwater analytical samples will be collected from the injection well and the groundwater monitoring wells in the demonstration area (See Table 1). During this sampling event, groundwater samples will be collected and analyzed for a variety of organic and inorganic parameters in order to characterize the existing biogeochemical environment in the aquifer. Analyses will include field parameters, electron acceptors, potential biodegradation byproducts and end products, other biogeochemical indicators, and laboratory analyses that focus on perchlorate and the USEPA Method 8260 analytes carbon tetrachloride, chloroform, trichloroethene, 1,2-dichloroethene, vinyl chloride, 2-butanone (methyl ethyl ketone), and 4-methyl-2-pentanone (methyl isobutyl ketone). Details regarding the various analyses to be performed are presented below:

- Field Parameters - These parameters are measured at each of the wells in the field, and can be used to assist with the assessment of groundwater conditions for the biodegradation of the perchlorate. The field parameters include DO, ORP, pH, temperature, and specific conductance.

- Electron Acceptors - Analysis for the presence of electron acceptors will provide an indication of the relative levels of inorganic compounds present in the groundwater that act as alternate electron acceptors. An understanding of the cycling of alternate electron acceptors will permit ARCADIS to infer the dominant bacterial processes within the aquifer as the demonstration proceeds. Concentrations of electron acceptors in the facility groundwater before and after reagent injection will be compared to ensure the optimal reducing environment is maintained in the subsurface. Electron acceptor analysis will include nitrate, sulfate, total and dissolved iron, and total and dissolved manganese.

- Potential Degradation Byproducts and End Products - Analysis for the degradation byproducts and end products will provide an indication of the relative levels of compounds formed through biodegradation and therefore can be used as an indicator of reductive dechlorination together with other observations. Byproducts and end products fall into several categories. Transient byproducts from the bacterial reduction of perchlorate include chlorate and chlorite. Also, depending on the electron donor loading, undesirable organic molecules such as alcohols and aldehydes can be formed within an IRZ as a result of excessive fermentation processes. Lastly, reduced inorganic species such as ferrous iron and sulfide are sometimes a part of the changed aquifer chemistry associated with IRZ implementation. Their presence and concentration during IRZ implementation can depend both on the type and amount of electron donor substance used and the background availability of iron and sulfur in the aquifer. Small quantities of chloride will be liberated as a final breakdown product of perchlorate. Although heavy metals are not "products" of IRZ implementation, care must be taken when dosing the IRZ not to encourage excess fermentation of electron donor sugars as this will lead to the formation of low molecular weight organic acids which can lower pH values in poorly buffered aquifers. Lower pH values can correlate with the dissolution and release of heavy metals from aquifer solids where they are naturally present in the groundwater.

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Table 1. Analytical Parameters and Schedule for Perchlorate *In Situ* Reactive Zone Pilot Study
Jet Propulsion Laboratory, Pasadena, California

Parameters	EPA Analytical Method	Baseline	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
Injection Events: Groundwater			1																	2			3			
Soil			1																	2						
Monitoring Event: Baseline		Bas																								
Progress				P1		P2		P3		P4							P5		P6	P7	P8		P9	P10	P11	
Performance																		Per1				Per2				Per3
Number of Injection Wells to Sample (X):		1																1				1				1
Number of Groundwater Monitoring Wells to Sample (T):		4																4				4				4
Number of Vadoze Zone Monitoring Wells to Sample (L):				2		2		2		2							2	2	2	2	2	2	2	2	2	2
Field Parameters																										
Dissolved oxygen	Field Instrument	XT		XTL		XTL		XTL		XTL							XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL
Oxidation reduction potential (ORP)	Field Instrument	XT		XTL		XTL		XTL		XTL							XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL
pH	Field Instrument	XT		XTL		XTL		XTL		XTL							XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL
Temperature	Field Instrument	XT		XTL		XTL		XTL		XTL							XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL
Specific conductance	Field Instrument	XT		XTL		XTL		XTL		XTL							XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL	XTL
Laboratory Analysis																										
Perchlorate	314	XT																XTL				XTL				XTL
VOCs (project specific list)	8260	XT																XTL				XTL				XTL
Dissolved Organic Carbon (DOC)	EPA 415.1	XT																XTL				XTL				XTL
Biological Oxygen Demand (BOD)	EPA 405.1	XT																								XT
Chemical Oxygen Demand (COD)	EPA 410.4m	XT																								XT
Total Dissolved Solids	160.1	XT																								XT
Chloride	300.1	XT																								XT
Nitrogen	351.3	XT																								XT
Phosphorus	365.2	XT																								XT
Dissolved Carbon Dioxide	SM4500	XT																								XT
Methane	RSK175	XT																								XT
Title 22 Metals	6010B	XT																								XT
Aldehydes	8315	XT																								XT
Manganese	6010B	XT																								XT
Alcohols	GC/FID	XT																								XT
Ferric Iron	6010B	XT																								XT
Sulfate	EPA 375.4	XT																								XT
Nitrate	EPA 353.3	XT																XT				XT				XTL
Sulfide	EPA 376.2	XT																								XT
Bromide	320.1	XT																XT				XT				XTL

Bas - Baseline sampling
P - Progress sampling
PER - Performance sampling

X - Indicated number of injection wells will be sampled for listed parameters.
T - Indicated number of monitoring wells will be sampled for listed parameters.
L - Indicated number of vadoze zone monitoring wells will be sampled for listed parameters.

- Other Parameters - Other parameters to be analyzed include alkalinity, DOC, bromide, chemical oxygen demand (COD), biological oxygen demand (BOD), perchlorate, and USEPA Method 8260 analytes carbon tetrachloride, chloroform, trichloroethene, 1,2-dichloroethene, vinyl chloride, 2-butanone (methyl ethyl ketone), and 4-methyl-2-pentanone (methyl isobutyl ketone). The DOC analysis measures the presence of organic carbon in the groundwater and will be used to assess the distribution of the injected electron donor. Bromide is added to the electron donor solution as a conservative tracer to provide a mechanism to track the electron donor dispersion within the aquifer. COD and BOD are required analyses under the provisions of the General Waste Discharge Permit adopted by the RWQCB and are included to meet the technical requirements of the permit. These parameters provide an indication as to the availability of organic carbon in the subsurface. Perchlorate analysis will provide information as to the condition of groundwater prior to commencing treatment. Perchlorate analysis after IRZ implementation will be utilized to evaluate the performance of the technology being demonstrated. The results of cVOC analyses to include carbon tetrachloride, chloroform, trichloroethene, 1,2-dichloroethene, vinyl chloride will allow for a direct assessment of any cVOC degradation that may occur during the pilot study.

The analyses planned for baseline data collection is summarized in Table 1. Analytical methods and field parameters are also covered in Table 1. Sample container requirements, holding times, and preservatives are covered separately in the Sampling and Analysis Plan (SAP) for this project.

3.10.3 Progress Monitoring Data Collection

Following completion of the baseline sampling event and initiation of carbohydrate solution injections, several groundwater sampling events will be conducted to monitor the developmental progress of the *in situ* reactive zone and assess the performance of the pilot study. The results of progress monitoring events will be used to judge when to perform more extensive analytical testing and when to initiate additional electron donor injection events as needed. It is anticipated that the pilot study will operate for a period of approximately 12 weeks. Progress monitoring events will be conducted at least weekly. During the first weeks of the pilot test, progress monitoring is expected to occur more frequently (between 2 and 3 times per week). Once the reactive zone has been established the progress monitoring events may be reduced in frequency.

Each progress monitoring event will include measurement of DO, ORP, pH, and specific conductivity. Due to their reactivity with the atmosphere, sulfide and ferrous iron will be measured in the field using a portable colorimetric method (HACH™ spectrophotometer). A field kit will also be used to monitor nitrate concentrations.

The target concentrations or ranges for various field parameters that will be used to measure and control progress and performance are as follows:

- pH – greater than 5.0 standard units (s.u.) in the injection wells; greater than 6.0 s.u. in the monitoring wells;
- DO – less than 1 mg/l in both monitoring and injection wells;
- ORP – greater than -200 mv and less than -50 mv in the injection wells; less than -50 mv in the monitoring wells;
- Specific conductance – up to an order of magnitude increase in the injection wells; up to 20 to 50 percent increases in monitoring wells.
- Temperature is monitored as part of the sampling protocol to determine if parameters have stabilized and a representative sample can be obtained. Temperature should not deviate more than 10% during three successive measurements during a sampling event prior to collecting a sample.

3.10.4 Performance Monitoring

Performance monitoring events have been scheduled every four weeks over the course of the pilot study. These monitoring events will include samples collected for analysis of perchlorate, cVOCs to include carbon tetrachloride, chloroform, trichloroethene, 1,2-dichloroethene, vinyl chloride, and DOC as well as the analytes required to meet the technical requirements of the General Waste Discharge Permit adopted by the RWQCB. Perchlorate analysis will provide direct evidence as to the effect the reducing conditions are having on the concentration of the target analyte. ARCADIS intends to monitor cVOCs to include carbon tetrachloride, chloroform, trichloroethene, 1,2-dichloroethene, vinyl chloride in order to determine cVOC fate in an IRZ dosed to achieve perchlorate treatment. Though ARCADIS employs the IRZ technology for cVOC treatment, the details of its implementation for cVOCs are different from those associated with perchlorate treatment. However, it is possible that some cVOC removal will be achieved simultaneously with perchlorate treatment. The inclusion of cVOCs to include carbon tetrachloride, chloroform, trichloroethene, 1,2-dichloroethene, vinyl chloride in the analytical scheme for the demonstration will permit assessment of their fate in the perchlorate IRZ. DOC will be monitored to ensure that electron donor solution is being dispersed throughout the pilot area.

Bromide will also be analyzed as a means of determining the dispersion of the electron donor solution in the subsurface.

The anticipated results from the analyses are as follows:

Perchlorate:	Reduction in concentration over time directly following or accompanying the removal of nitrate from the subsurface groundwater and the creation of reduced conditions.
cVOCs:	The IRZ could potentially reduce cVOC parent compound such as trichloroethene or carbon tetrachloride concentrations producing lesser chlorinated daughter products.
DOC:	Increases in concentration in monitoring wells to a range of 100 to 1,000 mg/L.
Bromide:	Increases in concentration directly corresponding to the amount of carbohydrate solution added to the subsurface.
Nitrate:	Reduction in concentration over time to non-detectable levels.
Sulfate:	Potential exists for sulfate to decline in concentration.
Ferrous iron:	Increased concentrations expected in the anaerobic IRZ.
Manganese:	Potential exists for manganese II to increase in concentration.
BOD:	Increases in concentration in monitoring wells corresponding to the increases observed for DOC analysis.
COD:	Response similar to that observed for BOD.

3.10.5 Compliance Monitoring

To ensure that adverse effects do not occur within the subsurface, monitoring well MW-7 will serve as a compliance point for the pilot study. This well is located downgradient from the injection well and has been monitored over the course of several quarters. This well will be monitored for ORP, pH, DO, specific conductance, temperature, cVOCs to include carbon tetrachloride, chloroform, trichloroethene, 1,2-dichloroethene, vinyl chloride, bromide, alcohols, aldehydes, Title 22 metals, and DOC to ensure that the treatment is occurring within the confines of the study area. Should well MW-7 begin to see impacts of the treatment process such as a consistent 2 to 3 unit decrease in pH or DOC in excess of 1,000 mg/L, then the injection of carbohydrate solution will cease and the well will be monitored to determine if the conditions begin to abate. Should they not abate, a provision for pumping well MW-7 has been included that would allow for capture of the injected solution before it could migrate away from the study area.

3.10.6 Final Monitoring

A final monitoring event will be conducted with analytes similar to that of the baseline monitoring event to determine the overall effectiveness of the pilot study. The final monitoring event results will be compared to the baseline results to evaluate subsurface changes in chemistry.

3.10.7 Composition of Electron Donor Solution and Tentative Injection Schedule

The first saturated zone electron donor injection will occur within ten days of the completion of well installation pending review of the baseline analytical data. Two hundred gallons of 15% weight/weight (wt/wt) solution of corn syrup will be added to the IW-1 screened interval within the saturated zone. This injection volume will include a bromide tracer at a concentration of 100 milligrams/liter (mg/L). It is ARCADIS' intent to create a perchlorate treating IRZ in the saturated zone to bring about treatment of any perchlorate that is flushed from the vadose zone source area during potential vadose zone injection events. After an anaerobic zone capable of treating perchlorate has been established in the saturated zone as a result of electron donor injection, ARCADIS will inject electron donor into the vadose zone at any depth interval(s) that are found to be perchlorate source areas using soil samples collected during well installation. Depending on the degree to which perchlorate is detected in the vadose zone, there is the potential for multiple one-time vadose zone injections. Vadose zone electron donor injections will consist of 1,000 gallons of 2% wt/wt solution of corn syrup per vadose zone screened interval with bromide present at a concentration of 100 mg/L as a tracer. If injected fluid is collected in any of the sumps installed in the vadose zone monitoring wells, ARCADIS will determine the ratio of corn syrup to bromide and compare it to the ratio of corn syrup to bromide known to be present at injection. This comparison will permit a more thorough understanding of corn syrup utilization in the vadose zone. Baseline analytical data and analytical data for samples collected subsequent to the initial injection events will be used to schedule additional saturated zone electron donor injection events. Currently, one vadose zone and three saturated zone electron donor injection events are contractually planned.

Saturated-zone injections will be completed using a down hole tubing ("stinger") assembly to deliver the reagent to groundwater at the base of well IW-1. A packer assembly will not be used for groundwater injections because the targeted screen interval is at the bottom of the well. In addition, packer decontamination between injection events will not be required if the assembly does not come into contact with impacted groundwater.

Vadose zone injections that are warranted by site conditions will be completed in injection well IW-1 using a down hole inflatable discrete-zone well bore packer assembly. The packer consists of two air-inflatable bladders that can be positioned above and below a screened interval that is to be isolated for injection. Using a truck-mounted well sampling rig, the packer will be lowered into the IW-1 well casing and inflated to isolate the screen for reagent injection. If multiple vadose zone screens are to receive injections, the deepest screen interval will be the first to be injected. Once the reagent is delivered between the bladders, the packer is deflated and moved up to the next screen interval. This sequence will be completed until each screen interval receives the prescribed reagent dosage for each injection event.

4. Definition of Success Criteria

ARCADIS is undertaking this perchlorate bioremediation demonstration with the intent to initiate and accelerate *in situ* perchlorate remediation in the saturated zone. If perchlorate source areas are delineated in the vadose zone, ARCADIS will initiate treatment of these source areas as a secondary goal of the demonstration. Of the two objectives, the bioremediation of perchlorate in the saturated zone is considered the most straightforward. Reduction in vadose zone perchlorate mass can be expected to greatly simplify and accelerate the pace of downgradient remediation measures aimed at the JPL dissolved phase perchlorate plume. Additionally, if feasible, *in situ* treatment of vadose zone perchlorate mass will require minimal interruption of ongoing research activities at the JPL facility.

With regard to defining success for bioremediation of perchlorate in the saturated zone, ARCADIS believes that clean-up to the 4 µg/L Action Level is achievable. Four years of data showing perchlorate concentrations is available for MW-7. Comparison of saturated zone perchlorate concentrations in groundwater samples collected from demonstration wells that are upgradient of MW-7 will permit an accurate assessment of IRZ performance in the saturated zone.

The most scientifically meaningful method of evaluating vadose zone perchlorate bioremediation brought about during this demonstration is to compare pre-demonstration perchlorate soil concentrations with post-demonstration soil concentrations. Until the well installation is complete and the project team understands if vadose zone perchlorate bioremediation will be demonstrated, it remains undecided as to whether the expense and intrusion on research activities at JPL that post-demonstration vadose zone soil sampling represents is justified.

5. Reporting

5.1 Monthly Reporting

The purpose of monthly reports is to update NASA on the progress and results of the demonstration. Monthly reports are expected to contain updates on progress in the field as well as results obtained and any emerging challenges faced by ARCADIS during implementation of the demonstration. To facilitate distribution, monthly reports will be submitted by electronic mail. Monthly reports can be used by NASA to judge the percent complete status of ongoing tasks within the design of the demonstration project.

5.2 Final Report

5.2.1 Final Report Description

The final report will include a detailed description of the materials and methods employed during the demonstration. Included in the report will be all analytical data generated during the demonstration in tabular and graphical formats. The report will be submitted in draft format for review NASA prior to finalization. The final report will be in electronic and hard copy format at the request of NFESC personnel (the draft of this document is in electronic format only).

5.2.2 Summary of Cost Performance Criteria

Accurate and detailed records will be maintained of the costs associated with execution of this perchlorate bioremediation demonstration. This data will be of sufficient extent to allow for a reasonable projection of full-scale operational costs. The data will be segregated into normal project phases, including startup, operation and maintenance and demobilization steps. A life cycle cost analysis for the technology will also be developed.

ARCADIS' Harper Shuman accounting system will be used to track costs on this project. Costs will be segregated first into the tasks outlined in our proposal. Costs are then further automatically segregated for all items except labor into general ledger numbers. For example general ledger number 531.10 is field services, general ledger number 521.00 is telephone, general ledger number 511.10 is Car rental etc. The system also provides item-by-item detail that can be traced back to the individual purchase order or voucher. Labor costs can be detailed using the daily work description form, which provides a written textual record of the work that corresponds to a given labor hour charge. These daily work descriptions will be required for all of the field operations phases of the project. Using this information ARCADIS can conduct an analysis near the end of the project that attempts to separate the true operational costs of implementing the technology from the costs of documenting its performance in an NFESC demonstration project. This can be done for labor costs associated with document production tasks simply by making an engineering judgment of by what percentage the planning and reporting requirements for such NASA demonstration project exceed those of a normal federal remediation project. A similar percentage could also be derived comparing the requirements of any demonstration project to the documentation requirements of a private sector remediation project.

Labor for field activities can be examined on a case-by-case basis using the documentation provided by the daily work descriptions. Thus labor associated with additional samples that would be taken in a demonstration context but not during routine remediation can be segregated. A similar analysis can be performed on individual materials and subcontractor line items.

5.2.2.1 Startup Costs

The costs associated with the start up phase include the labor required to execute the engineering design and work plan preparation. Other costs include the capital costs for installation of injection wells and equipment required to inject the electron donor used for this technology. The costs that will be quantified during the initial implementation phase of the demonstration include the following:

- Work plan preparation, submittal and editing required for regulatory acceptance.
- Bid solicitations and subcontractor management.
- Supervision of field work, including drilling and construction subcontractors.

5.2.2.2 Operations and Maintenance Costs

The costs associated with the operation and maintenance phase include the labor required to inject the electron donor solution into the aquifer and to collect groundwater samples from the treatment area. Other costs include groundwater sample analyses, and electron donor itself. The number of field personnel and the amount of time required for each injection event will be recorded.

Regular sampling of monitoring wells in the treatment area will be performed to quantify and validate the efficacy of the technology. Field equipment will be used to gather a portion of the monitoring data, and groundwater samples will be collected periodically for quantitative analyses. The number of personnel and the labor time expended in the monitoring and sample collection efforts will be recorded. Groundwater samples will be shipped to an off site laboratory for analysis, and all costs for transportation and analytical result reporting will be recorded. The amount of electron donor solution and carrier water injected will be recorded for each event, as will the costs for materials. Waste disposal costs will be considered an operational cost for the technology.

5.2.2.3 Demobilization

Following the execution of the demonstration, the costs required to decommission the remediation process will be recorded. This will include the labor and subcontractor costs required to remove any equipment or surface facilities associated with the demonstrations. It is anticipated that injection and monitoring wells will not be removed in the demonstration decommissioning process. Well abandonment will not be required until completion of the full-scale remediation. The wells installed during the demonstration will be available for use during the full-scale remediation or further treatment efforts. Minimal site restoration is anticipated, but any costs incurred will be tracked and documented.

5.2.2.4 Life-Cycle Costs

Comparing the costs for each project component/phase with a projection over the anticipated time required to complete the project will develop an estimated life-cycle cost for the IRZ perchlorate treatment technology. This financial analysis will provide the data required to more accurately estimate the potential to conserve remediation funds by investing capital to limit short-term environmental liability. Long term liability associated with perchlorate is not anticipated to be included in this fiscal analysis because perchlorate is essentially destroyed with the IRZ process, and therefore does not represent continued environmental liability.

The life-cycle cost projection will include the following:

- Capital cost.
- Project phase cost breakdowns.
- Startup.
- Laboratory Microcosm Study
- Operations and maintenance.
- Decommissioning.
- Regulatory interaction cost.
- Institutional control and long term monitoring costs.

One advantage of the IRZ technology compared to other remediation options is the substantial flexibility that is realized over the project life-cycle. An inherent challenge to any *in situ* remediation design is providing sufficient flexibility to adapt to changing conditions over time. The conditions in the aquifer will be dramatically changed upon initiation of an effective remediation system, and the degree and extent of chemical mass alteration is the primary means of measuring the efficacy of the remedial design. The most favorable remediation technologies allow for adjustments to be made to compensate for these changes, and to realize the most efficient remediation as alterations in the subsurface are established.

The IRZ technology is essentially a systematic introduction of an electron donor source into the aquifer. The amount of electron donor is adjusted during full-scale operation to match the mass of chemical, and the injection methodology is also adjusted to fit the treatment area as delineated by the monitoring data. This alteration of remediation process allows for the sequential scale-back of field labor and materials over time, and produces the most efficient means of destroying chemical mass.

This strategy will allow for a more accurate estimate of the life-cycle costs of the project by:

- Establishing at the onset of the project a strategy with built-in flexibility to adapt to anticipated chemical mass and distribution changes.
- Predicting the time period required for each stage of the remediation strategy.
- More accurately estimating the magnitude of the remediation system over time.
- Adjusting the remediation design to compensate for chemical mass and distribution changes and realize operation and maintenance cost savings.
- For this demonstration project, ARCADIS will calculate and report the cost in dollars per unit area treated.

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